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DIRECT-SEQUENCE

SPREAD SPECTRUM SYSTEM

THESIS

James P. Stephens, B.S.E.E.

AFIT/GE/ENG/90J-02

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DIRECT-SEQUENCE SPREAD SPECTRUM SYSTEM

THESIS

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Air University

In Partial Fulfillment of the

Requirements for the Degree of

Masters of Science in Electrical Engineering

James P. Stephens, B.S.E.E.

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Abstract

The purpose of this study is to construct and evaluate the performance of a direct-sequence spread spectrum (DSSS) system. The system, based upon a previously published design, uses a special type of injection-locked oscillator called a "synchronous oscillator" for code synchronization. The DSSS system was constructed in a manner that provides a test-bed for demonstrating spread spectrum principles and allows researchers to evaluate their own sub-system design concepts.

The DSSS system, designed as a one-way link in the 420-450 MHz band, is constructed to operate in accordance with Federal Communications Commission rules and regulations pertaining to the Amateur Radio Service (Part 97). Unlike conventional DSSS systems which combine digital data with a pseudorandom (PN) code sequence, the system described here directly modulates an FM modulated carrier with the PN code sequence.

The criteria used for evaluation are synchronization time, processing gain, and probability of bit-error rate. Because the DSSS receiver uses an inexpensive and practical direct conversion process before despreading, the receiver lacks good sensitivity.

In spite of the limited range of the system, fundamental concepts of DSSS were evaluated, the measurements agreed favorably with theoretical values, and all research objectives were met.

DIRECT-SEQUENCE SPREAD SPECTRUM SYSTEM

I. Introduction

Background

Modern military radio communications users are becoming increasingly interested in minimizing the effects of jamming or lowering the probability of their messages being received by unintended persons. Spread spectrum modulation is among the methods used to provide protection from intentional or accidental interference and against unauthorized interception. A spread spectrum system is a communication system in which the signal transmitted occupies a bandwidth much greater than what is necessary to send the information. This concept of increasing the bandwidth of a communications signal runs contrary to the principles of conservation of bandwidth. However, the increased bandwidth, which is accomplished by means of a code independent of the information, provides the necessary advantages of anti-jam (AJ) capability and low-probability-of-intercept (LPI).

There are several techniques by which spread spectrum can be implemented. One technique is called "direct-sequence." In this study, direct-sequence spread spectrum (DSSS) is achieved by directly modulating a conventional narrowband frequency-modulated (FM) carrier by a high rate digital code. The direct modulation is binary phase-shift keying (BPSK). The high rate digital code is referred to as a PN (pseudo-noise) code because it exhibits random-like properties which are necessary for providing good spectral characteristics and security.

Objectives

The purpose of this study is to construct and evaluate the performance of one particular class of DSSS system that uses a synchronous oscillator for code synchronization. The system is constructed in a manner that allows a variety of DSSS concepts to be observed, studied, and evaluated. By using modular construction techniques, the system provides a flexible test-bed that is useful for evaluating sub-system design concepts. For example, the performance of a new spread spectrum subsystem design may be evaluated using a test-bed in which the other required subsystems are available and functioning. The DSSS system developed for this study provides this test-bed capability. In addition to allowing other researchers to evaluate their own design concepts, the DSSS system is also useful in illustrating DSSS spectra for various operating parameters and demonstrating how these design parameters affect system performance.

System Configuration

Construction of the DSSS system is based upon an article appearing in QST Magazine, May 1989, by Andre' Kesteloot (1:14-21). The system as described by Kesteloot is intended for use in the Amateur Radio Service - a radio-communication service of self-training, intercommunication, and technical investigation carried on by amateur radio operators solely for personal aim. For this study, several design modifications were required. The resulting DSSS system, shown in Figure 1, consists of a transmitter unit and a receiver unit. The transmitter consists of an FM exciter, a PN code generator, a double-balanced mixer (DBM), an RF amplifier, a bandpass filter, and an antenna. The receiver consists of an antenna, an RF preamplifier, a DBM, a PN code generator, a synchronous oscillator , and a narrowband FM receiver.

The DSSS system operates as a one-way link in the 420-450 MHz band with an output power of approximately 100 mw. It uses a process called the "stored reference" design approach, in which a replica of the PN code used for spreading the signal is contained within the receiver. The process of demodulation requires that the spreading PN code must be synchronized to the stored reference PN code. The process of synchronization is

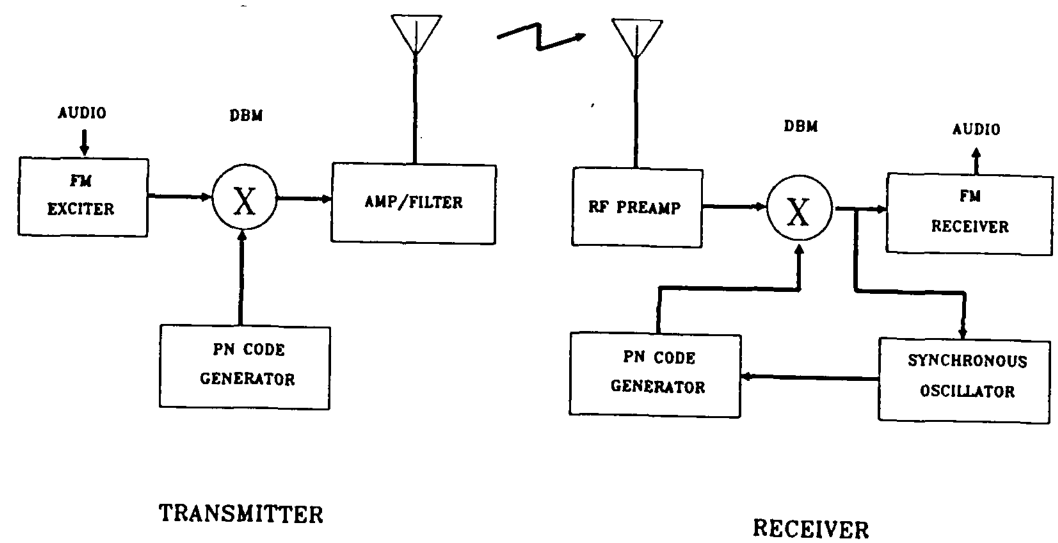


Figure 1. Basic Block Diagram of the DSSS System

accomplished by a special circuit called a synchronous oscillator. The capability of the synchronous oscillator to perform spread spectrum synchronization is evaluated in this study.

Regulatory Aspects

The operation of a radio transmitter, with a few exceptions, requires a license for the transmitter and usually the operator. In order for the system to be field tested, the DSSS system must be constructed in technical compliance with Federal Communication Commission rules and regulations pertaining to the Amateur Radio Service (Part 97). Therefore, the DSSS system described by this report may be legally operated by any person holding a Technician Class, or above, Amateur radio license. Such a license provides authorization for both the transmitter and the transmitter operator.

The regulations regarding operation in the Amateur Radio Service determined many of the operating parameters of the DSSS system. The most significant regulations are:

1. Only Amateur frequencies above 420 MHz may be used.
2. Harmful interference to other stations

may not result.

3. Only specific PN code sequences may be used.
4. Station identification must be given by narrowband emission at least every 10 minutes.

Appendix B provides detailed excerpts from Part 97 regarding the operation of spread spectrum in the Amateur Radio Service.

Scope

The design, construction, and evaluation of a spread spectrum system has enormous possibilities. Therefore, due to the constraints of time, it is necessary to place limitations on what will be accomplished in this research project. Those limitations are described here.

The design and construction of the DSSS system, in meeting the objectives of the research project, will be provided with capabilities suited for demonstration and for follow-on research activities. These special features will not be evaluated in this report. Only the performance of the basic DSSS system as described by the research objectives in this chapter will be evaluated.

In evaluating the DSSS system, the criteria used for determining system performance will be the processing gain, bit-error rate, and synchronization time. The methods used for determining these parameters will not be exhaustive. For example, an accurate determination of bit-error rate is not possible since variations of every other parameter affecting bit-error rate cannot be investigated. Also, only a limited number of measurements for a given set of circumstances can be taken. As a second example, the parameter of synchronization time is dependent on a variety of factors, such signal-to-noise ratio, code length, probabilities of false alarm and detection, and the time duration from the last synchronized transmission. It is not possible to investigate system synchronization performance under all possible conditions. However, what is attempted is to give the reader good insight into how well the synchronous oscillator performs synchronization and what are typical performance factors.

The capability of the DSSS system to operate successfully during field tests is also evaluated. Because field tests do not provide the opportunity for detailed analysis, observations rather than measurements will be reported. These observations will describe the ease by which synchronization is achieved and maintained, the intelligibility of speech, and the effects of narrowband interference.

A theoretical performance specification of the DSSS system will not be developed. The results of the evaluation phase of this research will be compared against theoretical determinations of optimal demodulation techniques. In the case of field tests, the results will simply be reported as observations.

Report Organization

This report provides a complete description of the DSSS system and evaluation results. Chapter II contains a brief discussion of the methodology used in deciding design criterion and test and measurement procedures used in the system evaluation. Chapter III provides a complete description of the overall system and the function of each subsystem. Chapter IV discusses the theory of operation, including a mathematical representation for the DSSS signal and the spread spectrum demodulation processes. Block and circuit diagrams are provided. Chapter V contains the results of the performance testing. Concluding comments and recommendations comprise Chapter VI. The Appendix provides detailed operating instructions for the DSSS system and excepts of Federal Communications Commission Rules and Regulations.

II. Methodology

The major objectives of this research effort relate to the design, construction, and the evaluation of a direct-sequence spread spectrum (DSSS) system. The process and procedures used to accomplish these objectives are described in this chapter. The additional objective of developing a test-bed for educational and research purposes, as described in chapter I, is somewhat incidental to the major objectives. The test-bed concept is easily met by careful consideration during system design and construction. Design decisions made for the purpose of accomplishing the test-bed objective will be appropriately denoted.

Design and Construction

The basic system design is based upon an article by Andre' Kesteloot appearing in QST Magazine (1:14-21). This configuration was selected because it is a practical spread spectrum system which can be reasonably constructed within the constraints of time and funding resources for a typical AFIT thesis.

Another important consideration which led to the design configuration proposed by Kesteloot relates to the regulatory aspects of operating a radio transmitter in free space (i.e. over the air.) In developing a spread spectrum system it was important that the final result be capable of actually radiating so that field tests could be performed as part of the system evaluation. Transmitter radiation in free space leads to the problem of insuring that the system is operating legally.

U.S. government agencies, including the military, generally do not require the licensing of radio transmitters provided they are used for official activities. Government and military transmitters do, however, require some type of authorization from a regulating authority. This authorization is necessary to insure the systematic operation of radio transmitters in a manner which will not cause interference to other stations. To accomplish this, there are governmental committees or military departments that establish frequency allocation standards and other guidelines of operation. These organizations coordinate their activities with the State Department, or in the case of non-governmental operations, the Federal Communications Commission. The problem of acquiring military or governmental authorization to operate a spread spectrum transmitter was considered arduous for a research activity of this nature. Therefore, in accordance with Kesteloot's article, the decision was made to provide for transmitter operation in the Amateur

Radio Service.

The Amateur Radio Service is ideally suited for experimental transmitter operation of this nature. Amateur Radio is a service regulated by the Federal Communications Commission for U.S. citizens to operate radio transmitters for hobby purposes, without business interests, to further the art of radio communications. Radio experimentation, such as this research project provides, is fundamental to the nature of the Amateur Radio Service (2:556-558).

Physical Layout. The article written by Kesteloot provides sufficient information to allow a person with experience in electronic fabrication to construct a similar system. However, the article did not provide many details. Furthermore, it was necessary to redesign several features of the DSSS system to more appropriately meet the objectives of this project.

One design decision was to construct only a single transmitter and receiver to establish a one-way communications link. Although not intended as part of this study, another transmitter/receiver pair could be constructed to provide a two-way communications capability. Both the transmitter and the receiver were constructed on separate 19 inch rack panels measuring seven inches in height. Due to the research objective to use modular construction, no attempt was made to make the system compact. In fact, excessive space is desireable to allow for later modifications and expansion.

The transmitter and receiver front panels are arranged in an organized manner so that others may easily operate and demonstrate the system. Most of the sub-assembly RF connections are brought out to the front panel to provide access to these stages for experimentation and measurement. Accessibility to these sub-assemblies is consistent with the test-bed concept. Overall, sound construction practices were followed to ensure a reasonably rugged installation that should last for many years.

Preassembled sub-assemblies were used to the extent possible to ease construction and to assure proper operation within the required tolerances of successful transmitter and receiver operation. The use of preassembled units allows more concentrated effort on the overall objective of system development. If preassembled units were not used, the time for system construction would be greatly increased.

Preassembled units used in the DSSS system are the narrowband FM exciter, the narrowband FM receiver, the receiver RF preamplifier, the transmitter helical filter, and both transmitter and receiver power supplies. Sub-assemblies constructed during this effort are the PN (pseudo-noise) code generator, the synchronous oscillator, the divide-by-40 circuit, and the double-balanced mixer assemblies for both the transmitter and receiver.

PN Code Generator. The PN code generator as described by Kesteloot was not used in the DSSS system (1:14-21). A redesigned generator was necessary to meet the research objective of providing an educational and research capability. The PN code generator was designed to provide full polynomial programmability up to, and including, degree-12 linear recursive sequences. The details of this redesign are fully described in Chapters III and IV. Several special features are included in the PN code generator design to allow for additional flexibility that is actually not required for this study. These features were included because they may be useful for the demonstration of spread spectrum features or for follow-on studies.

The PN code generator required the use of digital circuit design and printed circuit board layout techniques. Industry standards and manufacturer recommendations were used in the design and layout of the PN code generator and circuit board (3:4-7).

Synchronous Oscillator. The synchronous oscillator is a critical sub-assembly that requires exacting oscillator design and construction. A complete theoretical description of synchronous oscillators is provided in an article by Uzunoglu and White (4:1214-1225). The oscillator construction required hand winding of two inductors and careful attention to RF printed circuit board layout (3:4-7).

Double-balanced Mixers. The receiver double-balanced mixer requires one stage of RF amplification before the mixer and another stage of amplification following the mixer. The mixer operates at 446 MHz, requiring strip-line RF circuit board layout design techniques. Strip-line RF circuit design was necessary at this frequency to ensure proper impedance matching for the amplifiers to operate efficiently. The transmitter double-balanced mixer sub-assembly is not as complex as the receiver mixer since no amplifiers are required. The mixer component was simply mounted on a circuit board along with a variety of resistors which comprise attenuator networks at each of the mixer input and output ports (3:4-7; 5:3-7).

Tests and Evaluation

There are two aspects of the DSSS system test and evaluation. One aspect relates to conducting laboratory tests and evaluation where controlled measurements were accurately performed. The laboratory is where proper system operation was confirmed. In the laboratory a variety of waveforms were examined at various stages of the system, including between sub-assemblies. The other aspect concerns field testing and evaluation. Field tests occur when the transmitter and receiver are taken outdoors, separated by known distances, and operated under actual conditions. The ability of the system to properly operate under these conditions was verified. Field tests do not allow for scrutiny with external instrumentation that the laboratory environment provides. Therefore, the results reported from field tests are primarily observations rather than those of measurements as reported from laboratory tests.

Laboratory Tests and Evaluation

In the laboratory tests, the criteria used for evaluating the DSSS system were:

1. A comparison of measured system processing gain against a theoretical value.
2. A comparison of measured bit-error rate against a theoretical value.
3. A measurement and observation of synchronization time and performance.

Processing Gain. In a spread spectrum system, the processing gain is generally the most important factor in determining the ability of the system to perform in a jamming environment (6:57-61). The processing gain is easily computed theoretically by forming a ratio of the spread spectrum bandwidth to the narrowband signal bandwidth, that is:

$$G_p = B_{ss} / B_D \tag{1}$$

where

B_{ss} = bandwidth of the spread spectrum signal (Hz)

B_D = minimum bandwidth to send information (Hz)

This theoretical value is compared to a measured value. The measured value is determined in the laboratory by measuring the signal-to-noise ratio at the input to the receiver and forming a ratio to the signal-to-noise ratio at the demodulated output of the receiver (6:57-61). A null-to-null bandwidth was assumed for the spread spectrum signal bandwidth and a bounded power spectral density bandwidth (4 kHz) was assumed for the analog voice channel.

Bit-error Rate. Most operational spread spectrum systems transmit digital messages. The DSSS system is different in that the messages are analog in nature, such as speech or audio frequency shift keying (FSK). Audio FSK is normally the means by which digital information is transmitted over telephone lines. A modem converts the binary elements to frequency components which are carried over the phone lines as audio tones. In a similar fashion, digital information is transmitted by the DSSS as audio tones. FSK is used by the DSSS to transmit digital information for the purpose of measuring bit-error rate. A determination of the probability of bit-error rate versus signal level is performed at various data rates. The statistical nature of this type of measurement would require hundreds or thousands of repeated measurements to insure accurate results. This is beyond the scope of the current effort. Only an approximate determination of bit-error rate was made based on a small number of measurements. These results are compared to theoretical values in chapter 5 (7:15-27; 8:555-601).

Synchronization. The most difficult function of a spread spectrum system is achieving and maintaining synchronization (7:214-259). The synchronous oscillator technique used in the DSSS system is not an automatic technique as is commonly used in most operational spread spectrum systems. The synchronous oscillator may require manual adjustments in order to lock the stored reference code in the receiver to the transmitted code. There are advantages to using this manual technique and they are discussed in detail in chapter 4 (4:1214-1225).

The performance of the synchronous oscillator in achieving synchronization was evaluated. The evaluation criteria were the success of achieving synchronization, the time required for obtaining initial synchronization, and the time duration of maintained synchronization without the need for readjustment. These time measurements are also statistical in nature and only an approximation based on a small number of measurements was performed.

Field Tests and Evaluation

Field tests are controlled tests to the extent that communications are attempted at predetermined ranges at which signal levels have been previously calculated. The theoretical signal strengths were compared to observed signal levels. The ease of synchronization which was already verified during the laboratory tests were observed during the field tests. Also, the effect of narrowband interference on the DSSS system was observed. The criteria used for evaluating interference effects was the ability for the DSSS system to remain synchronized and to continue communicating with intelligible speech.

III. System and Subsystem Description

This chapter provides an introduction to the DSSS system and a description of each of the subsystems. Photographs and illustrations are used to show construction detail to the extent possible. Background information is provided to insure a proper understanding of important technical details.

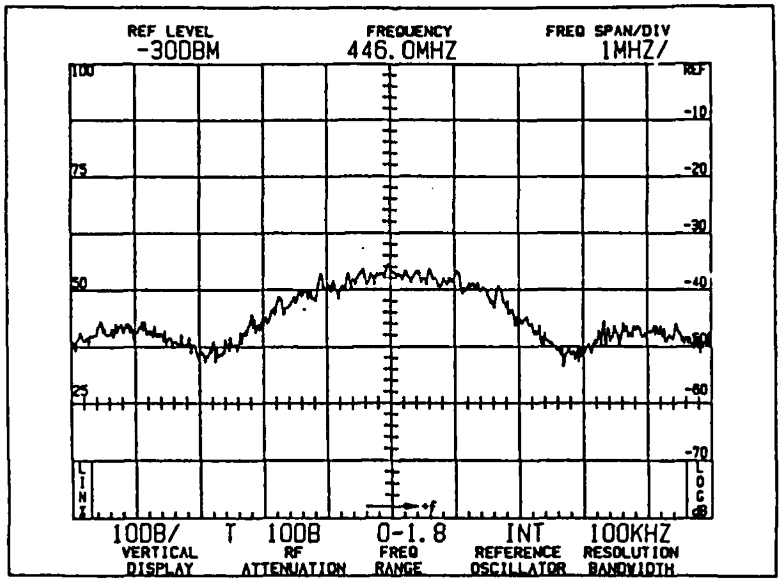
Definitions

As stated in chapter I, a spread spectrum system is a communication system in which the signal transmitted occupies a bandwidth much greater than what is necessary to send the information. The increasing of the bandwidth of a spread spectrum system is accomplished by means of a code which is independent of the information. Although there are several ways to implement spread spectrum, one method is called "direct sequence". Direct sequence can also be implemented in several ways. In this study, direct-sequence spread spectrum is achieved by directly modulating a conventional narrowband frequency modulated (FM) carrier by a high rate digital code.

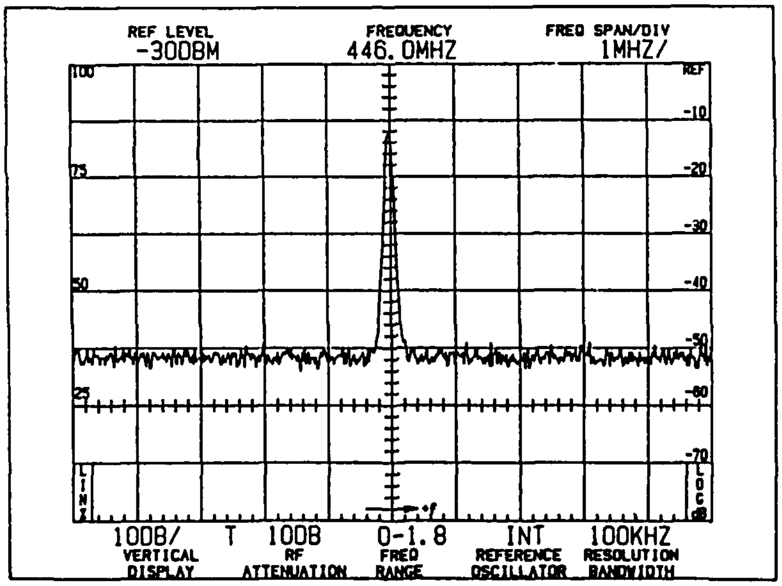
The direct modulation used in this study to produce direct-sequence spread spectrum is called binary phase-shift keying

(BPSK). BPSK is a modulation in which a binary "0" represents a 0-degree relative phase position of the carrier and a binary "1" represents a 180-degree relative phase position of the carrier. It is the high rate digital code that produces the "0"s and "1"s which cause the pseudo-random switching of the carrier between the 0 and 180-degree relative phase positions. This high rate switching spreads the transmitted bandwidth beyond that of the conventional narrowband FM signal. The amount of spreading is proportional to the rate of the digital code.

The high rate digital code exhibits pseudo-random properties which are necessary to provide good spectral characteristics and security. Pseudo-random (PN) codes are used because they have random-like properties, can be easily generated, and are difficult to reconstruct by an unauthorized receiver. Figure 2 illustrates the frequency spectrum of the DSSS signal as compared to the conventional narrowband FM signal (1:1-9). Systems may vary, but a bandwidth increase of 1000 times is typical.



Direct-Sequence Spread Spectrum Signal



Conventional Narrowband Signal

Figure 2. Frequency Spectrum of a Direct-Sequence Spread Spectrum Signal

Basic System Description

The DSSS system, as previously described in chapter I, consists of a transmitter unit and a receiver unit. The transmitter consists of an FM exciter, a PN code generator, a double-balanced mixer (DBM), an RF amplifier, a bandpass filter, and an antenna. The receiver consists of an antenna, an RF preamplifier, a DBM, a PN code generator, a synchronous oscillator, and an FM receiver. The complete system is shown in Figure 3. The basic DSSS system shown in Figure 1 of Chapter I, is shown with additional detail in Figure 4.

The transmitter and receiver units may be separated any distance within the range of the system to provide a one-way communication link. The DSSS system is operated by setting up the receiver and transmitter at different locations. The transmitter and receiver are initialized by selecting a code pattern and programming the same PN code into each unit. A microphone or any other source of audio is connected to the transmitter. Both the transmitter and receiver are connected to their respective antennas. When power is applied to both units, transmission will begin when the push-to-talk button on either the microphone or the transmitter front panel is activated. The tune knob of the receiver must be rotated until the receiver PN sequence has locked to the transmitter sequence. The system

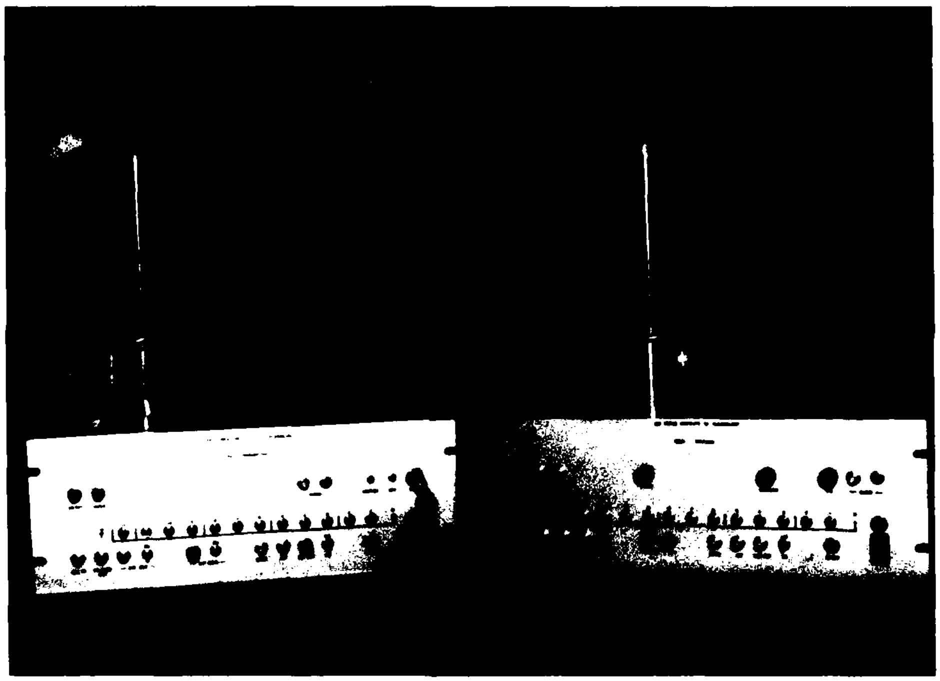


Figure 3. The DSSS System

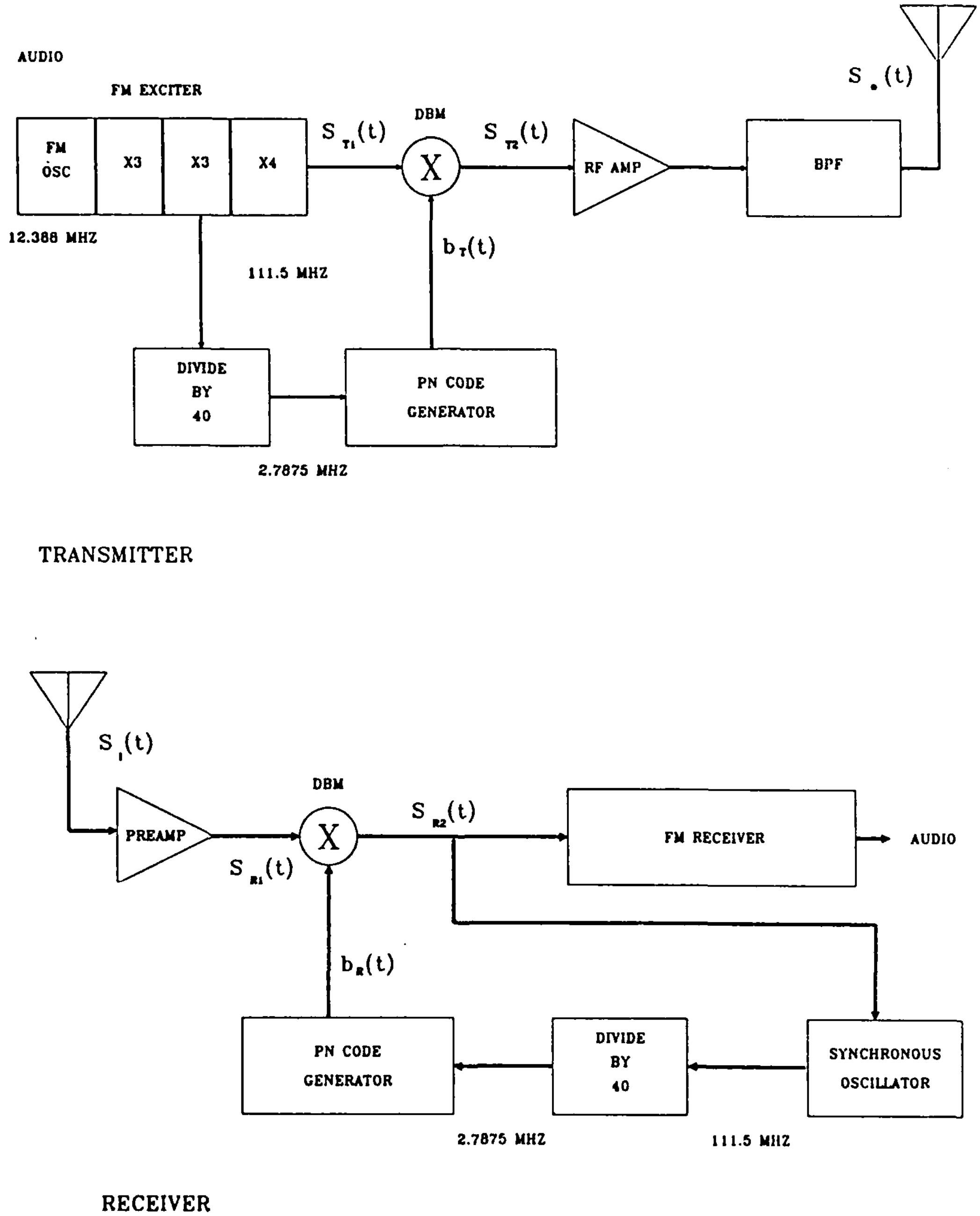


Figure 4. Detailed Block Diagram of the DSSS System

remains synchronized and speech or audio can be transmitted as long as the transmitter remains activated.

Transmitter

The transmitter unit contains the source of the radio frequency (RF) carrier which is modulated by the information source and spread by the PN code. The composite signal consisting of carrier, information, and code is amplified and sent to the antenna for radiation to the intended receiver. A pre-assembled power supply, which is not described in this paper, is also required to provide power to each of the basic subsystems. Figure 5 illustrates the relative position of each of the major transmitter subsystems described in this section.

FM Exciter

The FM exciter is a Hamtronics, model TA-451, UHF transmitter strip. The output of the TA-451 is reduced to 10 mw to serve as an exciter for the DSSS system. The TA-451 uses a 12.388 MHz crystal oscillator which is multiplied by 36 to produce an RF output at 446 MHz. Exciter energy at one-fourth the output frequency (111.5 MHz) is coupled to a divide-by-40 circuit to provide a clock source (2.7875 MHz) for the PN code generator. The TA-451 is designed to use a low-impedance dynamic

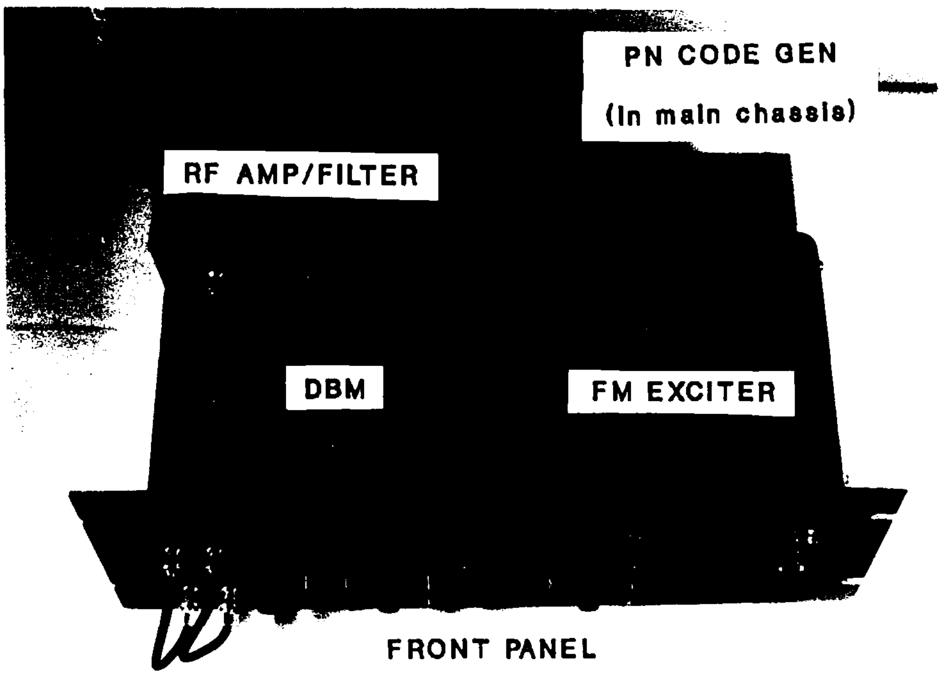


Figure 5. DSSS Transmitter Sub-assemblies

microphone, or any low impedance audio source, as the information source. The FM exciter is frequency modulated by the information source.

The FM exciter is constructed on a circuit board which measures 3.5 x 5.5 inches and is mounted inside a shielded aluminum box. The FM exciter power requirements are +13.6 vdc at 600 ma. A photograph of the Hamtronics TA-451 UHF FM exciter is shown in Figure 6. With the proper crystal, the TA-451 exciter may operate anywhere within the 400-470 MHz band, although additional tuning would be required.

Double-Balanced Mixer

The double-balanced mixer (DBM) is a Mini-Circuits, model SBL-1. The DBM combines the frequency modulated carrier with the PN code to produce a wideband DSSS signal. The DBM performs the function of multiplication of the PN code and the FM-modulated carrier. The DBM output is BPSK. The SBL-1 is mounted on a circuit board measuring 2.5 x 1.25 inches and is secured in a shielded aluminum box attached to the top of the main transmitter chassis. The DBM component is a passive device and requires no power source. A photograph of the DBM is shown in Figure 7.

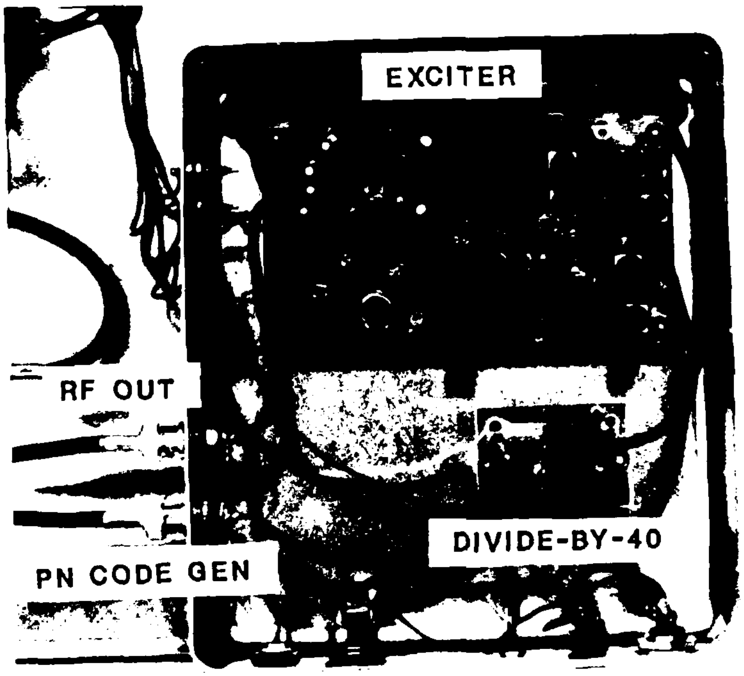


Figure 6. Hamtronics TA451 UHF FM Exciter

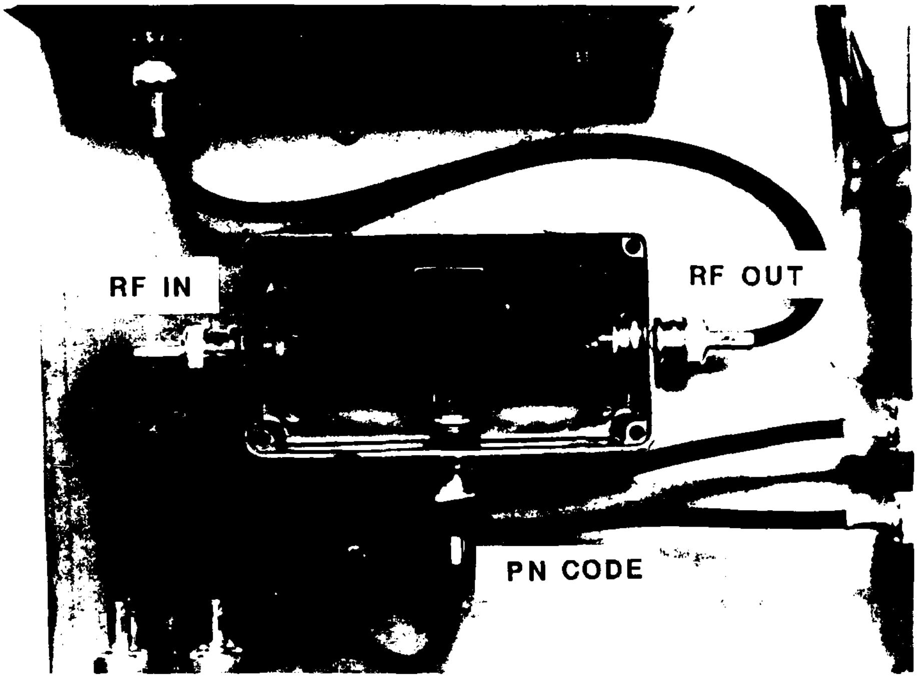


Figure 7. DSSS Transmitter Double-Balanced Mixer Assembly

PN Code Generator

The PN code generator provides the pseudorandom digital waveform that is used to spread the frequency modulated carrier to produce a DSSS signal. The PN code generator is designed to be programmable from the transmitter front panel. The PN code generator can output linear recursive sequences (LRS) for any polynomial up to, and including, degree-12. LRS are a class of PN codes which are generated by digital feedback shift-registers. A digital shift-register of degree-n is a device consisting of n consecutive binary storage elements. The PN code generator is clocked at the rate of 2.7875 MHz as derived from the FM exciter. The PN code generator consists of 21 7400-LS series transistor-transistor-logic (TTL) integrated circuits mounted on a double-sided circuit board which measures 5 x 10 inches. The PN code generator requires +5 vdc at 125 ma of power and is mounted inside the main transmitter chassis. A photograph of the PN code generator circuit board viewed from the underside of the transmitter is shown in Figure 8.

RF Amplifier / Filter

The power level of the DSSS signal outputted by the DBM is very weak and requires amplification. The RF amplifier is a Mini-Circuits, model ZFL-1000H. It provides approximately 30 dB

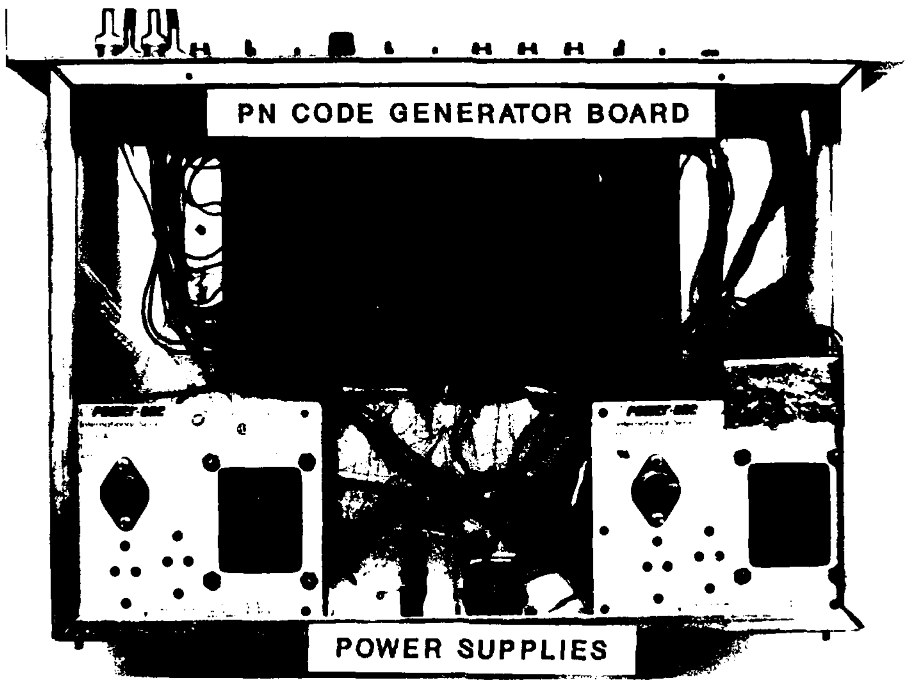


Figure 8. DSSS Transmitter PN Code Generator Assembly

of gain with a maximum output power level of 100 mw. The ZFL-1000H measures approximately 1 x 1 x 1 inches and requires +15 vdc at 150 ma of power. The ZFL-1000H is installed in a shielded aluminum box along with a Hamtronics, model HRF-432, helical resonator filter. The HRF-432 is used as a bandpass filter to attenuate the emissions below 442 MHz and above 450 MHz. Energy outside the 442-450 MHz band is unnecessary and will cause the final amplifier to operate less efficiently. The RF amplifier box is mounted on top of the main transmitter chassis. Figure 9 is a photograph of the RF amplifier and bandpass filter assembly.

Antenna

The antenna serves to interface the generated DSSS signal to free-space for transmission as electromagnetic waves. The UHF antenna is a Cushcraft, Ringo AR-450. The AR-450 is 15 inches long and mounted on a 10 foot mast during field tests. During set-up, the antenna and mast must be mounted as high as practical and in the clear of surrounding obstacles. The AR-450 is shown in Figure 10.

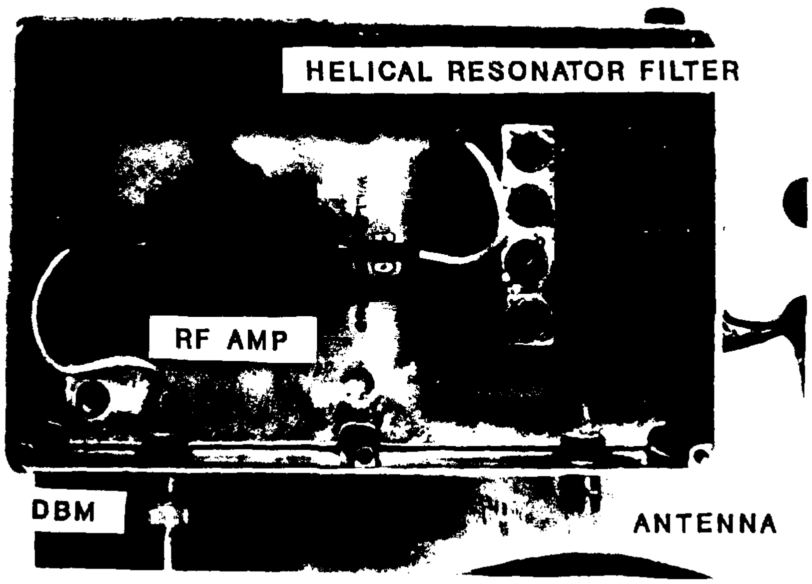


Figure 9. DSSS Transmitter RF Amplifier and Bandpass Filter Assembly

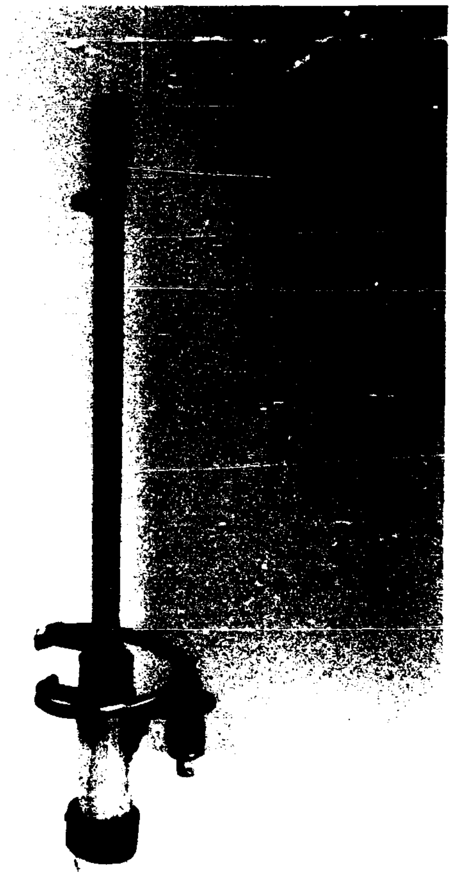


Figure 10. Cushcraft AR450 Ringo UHF Antenna

Special Design Features

The transmitter has several special design features which were added to help meet the objectives of developing a test-bed capability and to provide additional flexibility for demonstration and research activities. These features are:

1. An external clock input
2. An external digital data input
3. A synchronization pulse output at the code period rate
4. A chip rate output
5. An alternate PN code generator output
6. A spread spectrum disable switch

These features are more fully described in Chapter IV.

Receiver

The receiver unit performs the function of collecting the weak electromagnetic waves generated by the transmitter and converting the waves to a signal which can be processed. The signal processing will remove the spreading waveform so that demodulation can take place. Removing the spreading waveform requires synchronization of the received PN code to a replica of the PN code generated by the receiver. The process of demodulation will recover the original information. As with the transmitter unit, a preassembled power supply is required to provide power to each of the basic components. Figure 11 illustrates the location of each of the major receiver components described in this section.

Antenna

The antenna serves to interface the free-space electromagnetic waves to the receiver by developing a signal which represents the original DSSS signal. The same antenna type used by the transmitter is used by the receiver. The Cushcraft, Ringo AR-450, antenna and 10 foot mast must be mounted as high as practical and in the clear of surrounding obstacles. The AR-450 is shown in Figure 10.

RF Preamplifier

The RF preamplifier is required to boost the weak DSSS signal received by the antenna to a power level sufficient for processing. The preamplifier is a Hamtronics, model LNG-432, adjusted to provide a flat +18 dB response from 430 to 460 MHz.

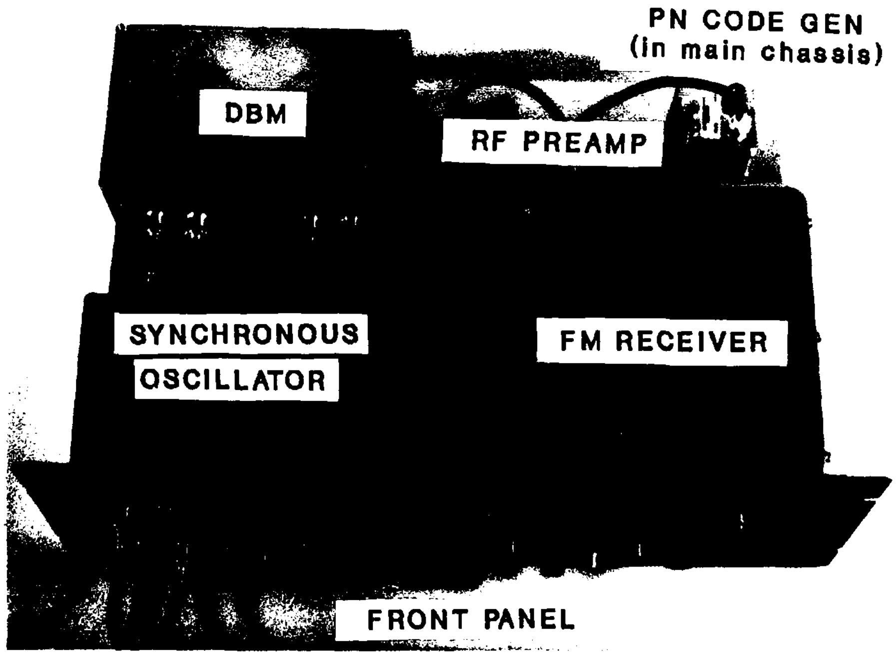


Figure 11. DSSS Receiver Sub-assemblies

The LNG-432 uses a dual-gate gallium arsenide (GaAs) field-effect transistor (FET) to achieve a noise figure of approximately 0.8 dB. The LNG-432 is self contained, measures 2 x 2 x 1.5 inches, and is mounted on top to the main receiver chassis.. The LNG-432 requires +13.6 vdc at 10 ma of power. Figure 12 shows the LNG-432 mounted in the receiver.

Double-Balanced Mixer

The receiver DBM combines the received and amplified DSSS signal with the synchronized PN code replica to produce a despread, narrowband, FM-modulated signal. The receiver DBM performs the function of multiplication of the PN code and the received signal. This multiplication acts to remove the spreading waveform. The DBM used in the receiver is identical to the DBM used in the transmitter, except the receiver DBM uses additional amplification before and after the mixing operation to overcome losses. The receiver DBM circuit board measures 2 x 4 inches and is mounted in a shielded aluminum box secured to the top of the main transmitter chassis. The receiver DBM requires +13.6 vdc at 20 ma of power. The receiver DBM is shown in Figure 13.

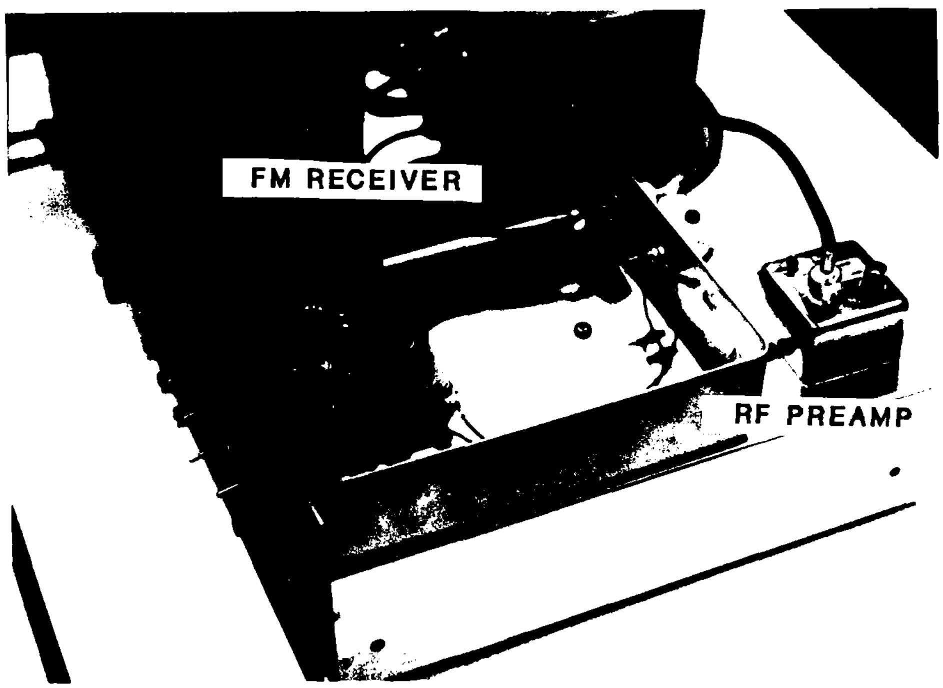


Figure 12. Hamtronics R451 UHF Receiver and LNG432 UHF GaAS FET Preamplifier

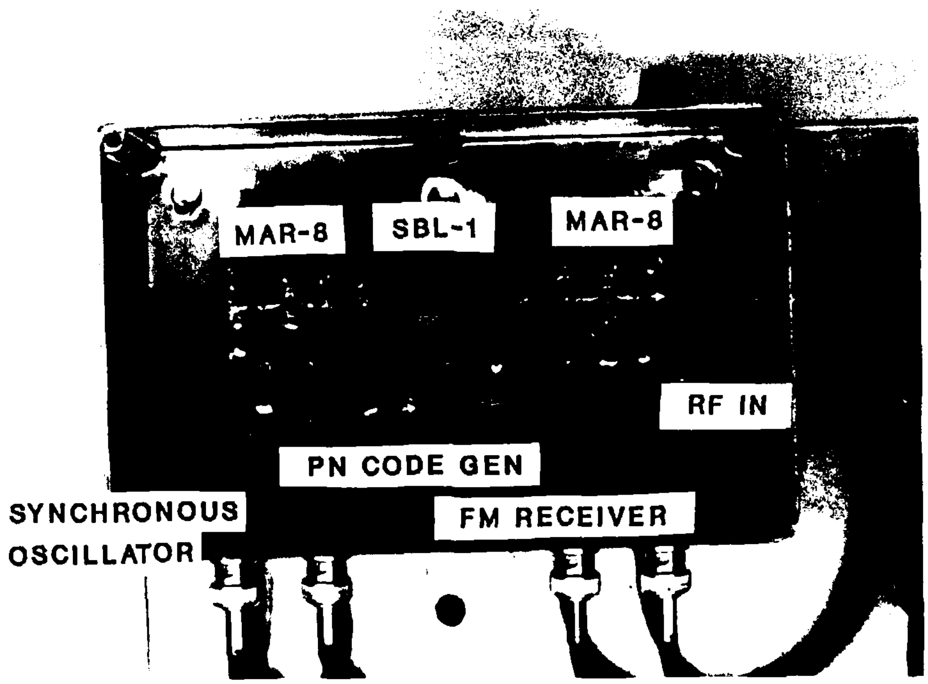


Figure 13. DSSS Receiver Double-Balanced Mixer Assembly

PN Code Generator

The PN code generator in the receiver unit provides the PN code replica used to despread the DSSS signal after synchronization has been achieved. The PN code generator used in the receiver is the same type used in the transmitter. The receiver PN code generator is clocked at the rate of 2.7875 MHz which is established by the synchronous oscillator. The PN code generator circuit board is mounted inside the main receiver chassis and is shown in Figure 14.

Synchronous Oscillator

The synchronous oscillator is a synchronization and tracking network used to align, in frequency and time, the PN code generated by the transmitter with the PN code generated by the receiver. The synchronous oscillator is a free running oscillator which resonates at a natural frequency of 111.5 MHz in the absence of an externally applied signal. The externally applied signal is taken from the output of the DBM. In the presence of a signal from the DBM, the oscillator synchronizes with, and tracks, the input to the DBM. The output of the synchronous oscillator is divided by 40 to produce a 2.7875 MHz clock signal for the receiver PN code generator. The divide-by-

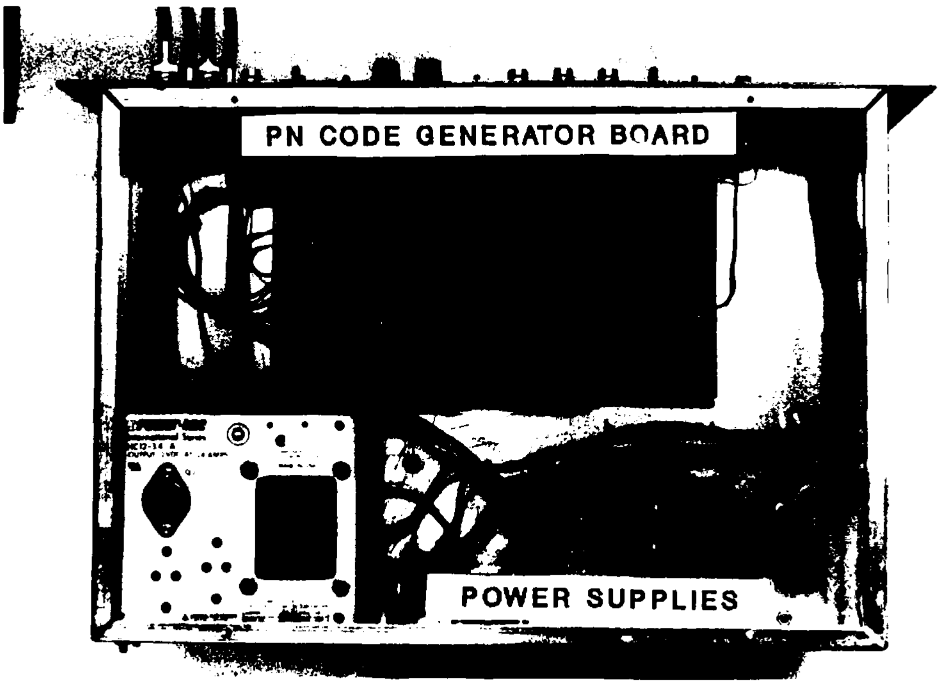


Figure 14. DSSS Receiver PN Code Generator Assembly

40 arrangement exactly duplicates that used at the transmitter. The synchronizing signal steers the synchronous oscillator to the precise frequency and code epoch to achieve and maintain synchronization. The synchronous oscillator is constructed on a printed circuit board measuring 2 x 4 inches which is mounted in a shielded aluminum box. The synchronous oscillator, shown in Figure 15, is attached to the top of the main receiver chassis and requires +13.6 vdc at 20 ma of power.

FM Receiver

The FM receiver performs the demodulation of the speech or audio source after the DSSS signal has been despread. The message is outputted to a speaker or some other external device such as a computer modem. The FM receiver is a Hamtronics, model R451, UHF receiver strip. It is assembled on a printed circuit board measuring 3.75 x 4 inches and mounted in a shielded aluminum box attached to the top of the main receiver chassis. The R451, shown in Figure 12, requires +13.6 vdc at 15 ma of power.

Special Design Features

The receiver has several special design features which were

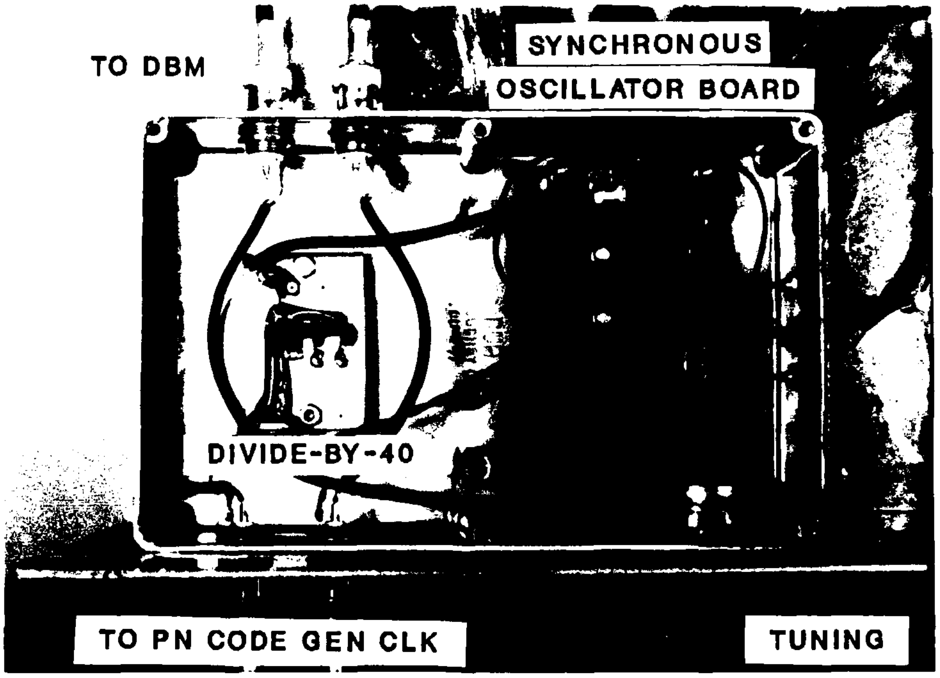


Figure 15. DSSS Synchronous Oscillator Assembly

added to help meet the objectives of developing a test-bed capability and to provide additional flexibility for demonstration and research activities. These features are:

1. An external clock input
2. FM discriminator and IF outputs
3. A synchronization pulse output at the code period rate
4. A chip rate output
5. An alternate PN code generator output
6. A spread spectrum disable switch

These features are more fully described in Chapter IV.

IV. Theory of Operation

This chapter provides a mathematical description of the DSSS system. The mathematical representation of the demodulation process discussed assumes perfect synchronization. The hardware implementation of the mathematical process is also provided for each major subsystem of the DSSS system. The emphasis regarding hardware implementation is on the spread spectrum aspects of these subsystems. Conventional RF assemblies are not discussed in detail. Circuit diagrams and signal waveforms are used to enhance technical description.

Transmitter

Mathematical Representation

Refer again to Figure 4 for the DSSS system diagram. The source of the RF carrier is the TA451, FM exciter. With no modulation

$$s_{T1}(t) = A \cos 2\pi f_0 t \qquad (2)$$

where,

f_0 = exciter frequency (446.0 MHz)

A = exciter amplitude (0.707 volts).

The exciter output is adjusted to provide 10 mw of power into 50 ohms (+10 dBm). The exciter signal may by FM modulated by the TA451 before spreading. With sinusoidal modulation the exciter output is (9:147)

$$s_{T1}(t) = A \cos (2\pi f_0 t + \beta \sin 2\pi f_m t) \qquad (3)$$

where,

β = FM modulation index

f_m = modulating frequency.

With arbitrary modulation, as in the case of speech, the exciter output is (9:145)

$$s_{T1}(t) = A \cos \{ 2\pi f_0 t + k \int_{-\infty}^{t} m(t)dt \} \qquad (4)$$

where,

m(t) = arbitrary modulation waveform

k = frequency deviation constant.

The TA451 will produce a maximum frequency deviation, Δf, of 5 kHz. The modulator is bandlimited to allow speech from approximately 50 Hz to 3500 Hz. Therefore, the modulation index becomes (9:147)

$$\beta = \Delta f / f_{max} = 5000 / 3500 = 1.43. \qquad (5)$$

The amplitude of the sinusoidal modulation and also m(t), is limited to 15 mv to produce Δf = 5 kHz. The frequency deviation constant becomes

$$k = 5000 \text{ Hz} / 15 \text{ mv} = 333 \text{ kHz} / \text{volt}. \qquad (6)$$

Audio FSK modulation can be represented by defining (9:276)

$$m(t) = B \cos (2\pi f_m t + d(t) 2\pi \Omega t) \qquad (7)$$

where,

B = modulation amplitude (30 mv p-p max)

f_m = modulation rest frequency

d(t) = digital data waveform (± 1)

Ω = constant frequency offset.

During audio FSK testing, the modem was configured such that

$$f_m = 2125 \text{ Hz}$$

$$f_1 = 2025 \text{ Hz } (+1), \quad f_2 = 2225 \text{ Hz } (-1)$$

$$\Omega = \pm 100 \text{ Hz.}$$

At the transmitter DBM assembly, $s_{T1}(t)$ is attenuated, multiplied by the PN code sequence, and attenuated again. The PN code from the generator is a TTL level (unipolar) signal and is converted to a bipolar signal (+A or -A) by passing through a capacitor. The dc-blocking capacitor acts as a rudimentary high pass filter. The 3 dB cutoff frequency for an RC, high pass filter circuit is (9:105)

$$f_{3db} = 0.5 \quad RC \quad = \quad 31.8 \text{ kHz} \tag{8}$$

where,

$$R = 50 \text{ ohms}$$

$$C = 0.1 \ \mu f.$$

The effect of this filter is to block the DC component of the PN code sequence; but since the code rate is 2.7875 MHz, waveform tilt is developed. Tilt is slope at the top of a rectangular waveform caused by poor low frequency response. Tilt causes a slight code imbalance which results in less than ideal carrier suppression at the mixer output.

Defining the PN sequence, b(t), as a stream of binary digits having voltage levels of ± 1; and assuming ideal waveforms, the mixer output without modulation becomes

$$s_{T2}(t) = \begin{cases} b_T(t)\ s_{T1}(t) & (9) \\ b_T(t)\ K_T\ A \cos 2\pi\ f_0 t & (10) \end{cases}$$

$$s_{T2}(t) = \begin{cases} K_T\ A \cos\ (2\pi\ f_0 t), & \text{for } b_T = +1 \\ -K_T\ A \cos\ (2\pi\ f_0 t), & \text{for } b_T = -1 \end{cases} \qquad (11)$$

or,

$$s_{T2}(t) = \begin{cases} K_T\ A \cos\ (2\pi\ f_0 t), & \text{for } b_T = +1 \\ K_T\ A \cos\ (2\pi\ f_0 t + \pi\ ), & \text{for } b_T = -1 \end{cases} \qquad (12)$$

where,

K_T = amplitude gain due to mixer amplifier, mixer losses, and $b_T(t)$ amplitude.

The PN code sequence, $b_T(t)$, used in this analysis has the following parameters:

r_c = chip rate = 2.7875 MHz

T_c = chip time = 362.5 ns

n = code sequence polynomial degree = 7

N = code sequence length = 127 bits

T_N = code period = N T_c = 46.04 μs.

The last two operations performed by the transmitter are final RF amplification and bandpass filtering. The output signal becomes

$$s_o(t) = \mathrm{BPF}\ \{\ b_T(t)\ K_T\ A \cos\ (2\pi\ f_0 t)\ \} \tag{13}$$

where,

BPF = denotes bandpass filter operation

$b_T(t)$ = PN code sequence ($\pm$ 1)

K_T = amplitude gain due to combined effects of final RF amplifier and bandpass filter loss.

$K_T A$, the final carrier amplitude, is approximately 0.5 volts (5 mw into 50 ohms (+7 dbm)).

The waveform of b(t) is a NRZ (non-return-to-zero) binary waveform. The sequence is periodic but can be approximated as a random sequence with power spectral density, shown in Figure 16(a), of (9:252)

$$G_b(f) = T_c\ (\ \sin\ \ f\ T_c\ /\ \ f\ T_c\ )^2\ . \tag{14}$$

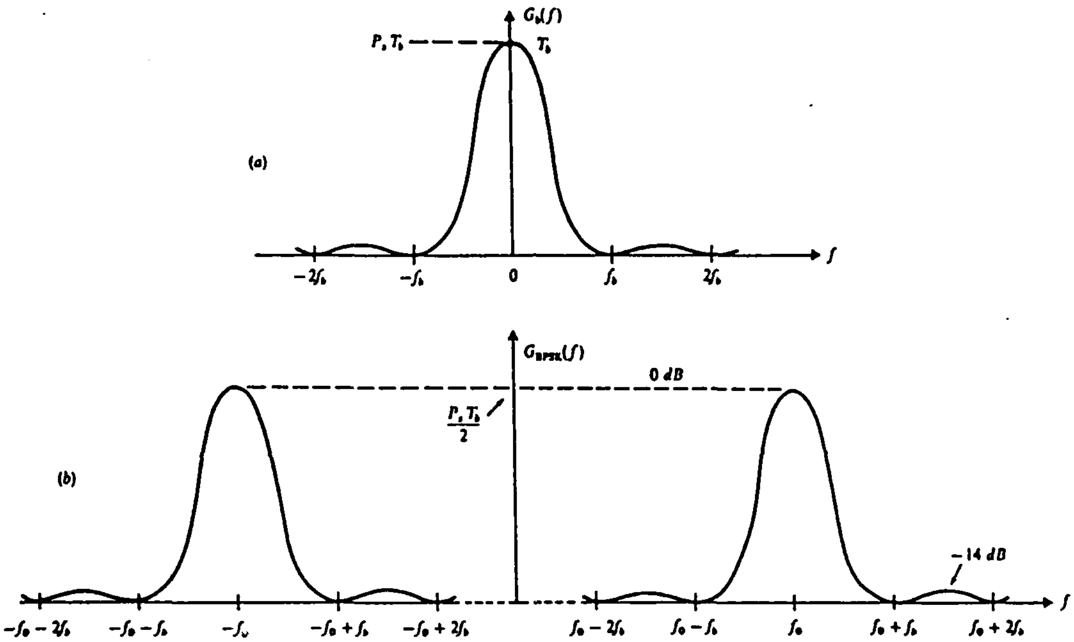


Figure 16. (a) Power Spectral Density of NRZ Random Code b(t)
(b) Power Spectral Density of DSSS (9:254)

With no modulation, the DSSS power spectral density for a truly random sequence, shown in Figure 16(b), is (9:253)

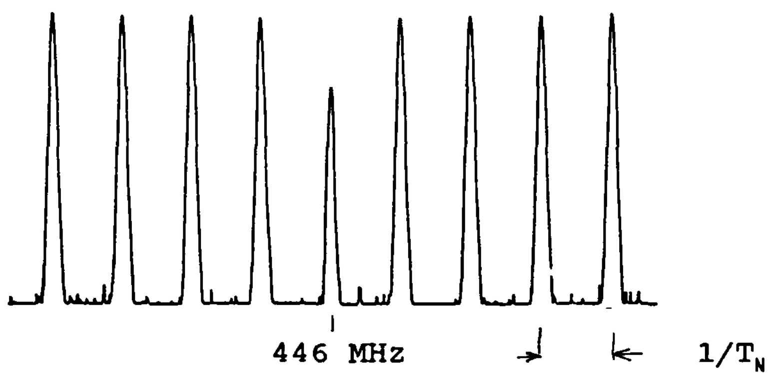
$$G_o(f) = \frac{P_s\, T_c}{2} \left\{ \frac{\sin\ (f - f_0)T_c}{(f - f_0)T_c} \right\}^2 + \left\{ \frac{\sin\ (f + f_0)T_c}{(f + f_0)T_c} \right\}^2 \quad (15)$$

where,

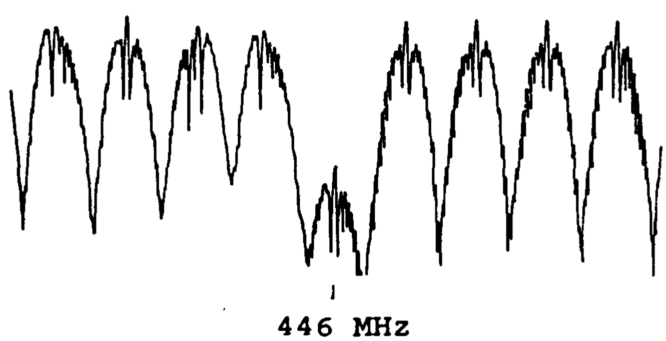
P_s = carrier power.

The PN code sequence is not random so $G_o(f)$ will not be continuous but will have discrete line spectra at $1/T_N$ intervals. This will be discussed in more detail in the PN code generator section of this chapter.

The effect of the narrowband modulation on the power spectral density is shown in Figure 17. Figure 17(a) shows discrete line spectra in the power spectral density of the transmitter signal without modulation. Figure 17(b) shows the effect of sinusoidal modulation, equation (3), on the DSSS power spectral density. Note the carrier suppression.



(a) No modulation



(b) Sinusoidal modulation

Figure 17. Effect of Narrowband FM Modulation on the Power Spectral Density of DSSS Signal

FM Exciter

The Hamtronics, TA451, exciter is a single-channel UHF FM transmitter which provides the RF carrier for the DSSS system. It is designed for narrowband frequency modulation with a 5 kHz maximum frequency deviation. The audio input is designed to accept a standard low-impedance dynamic microphone or any low impedance audio source capable of providing 15 mv peak into a 2000 ohm load. The operating frequency is established by a 32 pf parallel resonant crystal operating in fundamental mode of $f_0/36$. A crystal frequency of 12.388 MHz is used to provide a carrier at 446.0 MHz (10).

The TA451 schematic diagram is shown in Figure 18. Q4 operates as a Colpitts oscillator at the fundamental frequency of approximately 12 MHz. The precise frequency is established by the crystal resonant frequency. The oscillator output is fed into reactance modulator Q5, which phase modulates the carrier with audio from the speech processor circuits.

Q6 operates as a tripler to multiply the carrier frequency to approximately 37.167 MHz. Q7 triples again to 111.5 MHz. This signal is coupled to an external divide-by-40 circuit to provide a clock source, coherent with the carrier, to drive the PN code generator. Q8 and Q9 each double the 111.5 MHz signal to the final frequency of 446.0 MHz.

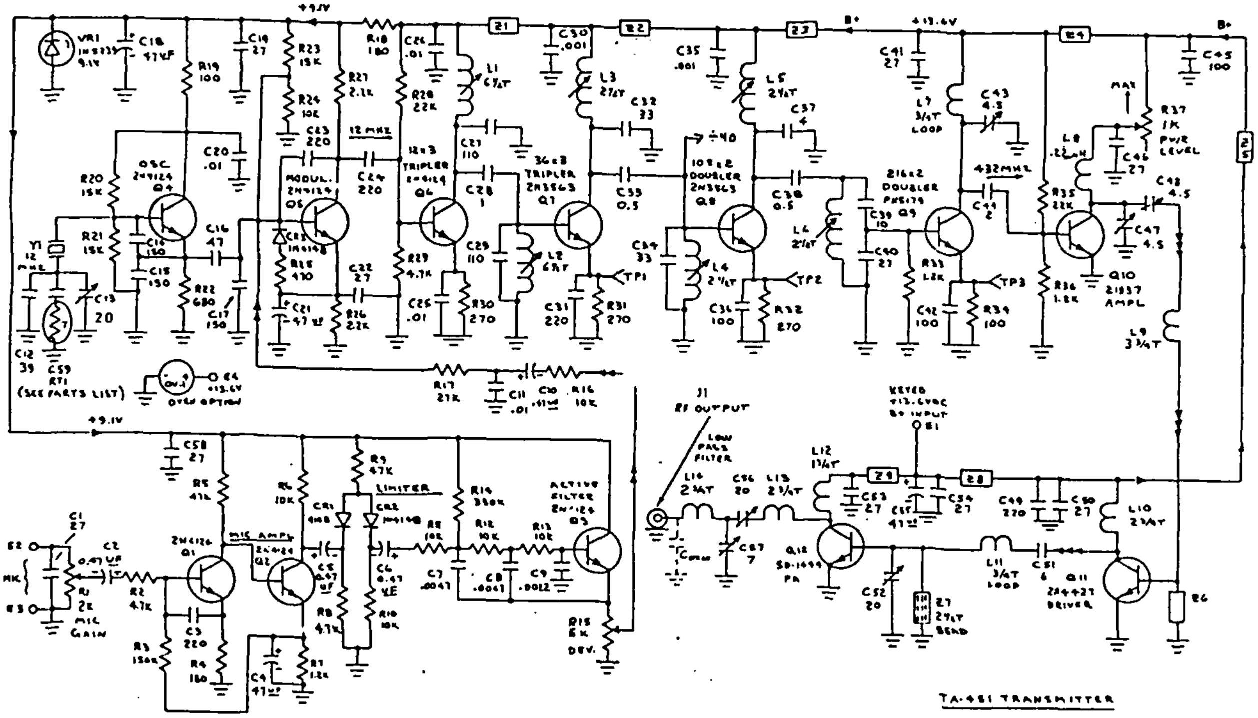


Figure 18. Hamtronics, TA451, Exciter Circuit Diagram (10)

Q10 is a predriver amplifier with R37 to adjust the collector voltage to set the drive level of the output stages. Q11 and Q12 are the driver and final amplifier to the 50 ohm output connector.

The audio processor circuits consist of a microphone amplifier (Q1 and Q2), peak limiter (CR1 and CR2), and an active filter Q3. The audio input is amplified and applied to the limiter. R1 provides adjustment of the audio gain. Normally 30 mv p-p provides 5 kHz frequency deviation.

Active filter Q3 is a low pass filter which reduces the effects of distortion from the limiter. This filter limits the bandwidth of the narrowband signal to approximately 20 kHz. R15 allows for adjustment of the peak audio level applied to the modulator. C11/R17 is an RF filter to keep the 12 MHz carrier from getting back into the active filter. R16/C11 acts as an additional lowpass filter. Altogether, the active filter stage provides 18 dB/octave rolloff for frequencies over 3 kHz.

The divide-by-40 prescaler, shown in Figure 19, uses a DS-8626 to divide down the 111.5 MHz exciter frequency from the base of Q8. This provides a 2.7875 MHz clock source that is coherent with the carrier. Such an arrangement ensures that the carrier is in-phase with the chip clock. That is, the carrier will be

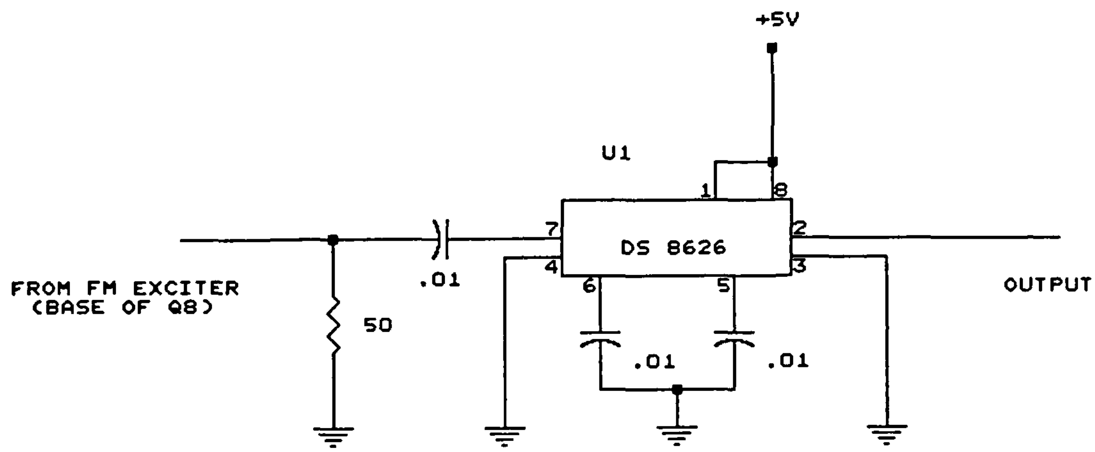


Figure 19. Divide-by-40 Prescaler Circuit Diagram

near a zero crossing when a chip transition occurs. To do otherwise will result in "needless and wasteful high frequency components (11: 12)." In the DSSS system, each code chip contains precisely 160 cycles of the 446 MHz carrier.

Double-Balanced Mixer

The transmitter double-balanced mixer (DBM) circuit is shown in Figure 20. This mixer assembly consists of a Mini-Circuits SBL-1 DBM, an attenuator at each mixer port, and a dc-blocking capacitor. Mathematically, the DBM performs the function of multiplication of the PN code sequence $b_T(t)$ by the exciter output signal $s_{T1}(t)$. Since $b_T(t)$ takes on values of ± 1, the effect is to leave $s_{T1}(t)$ unaffected (+1), or shifted by 180 degrees (-1). The mixer output is bi-phased shifted keyed (BPSK).

When a code is used to generate a spread spectrum output from a DBM, a great deal of care must be exercised to provide both carrier and code clock suppression. Figure 21 shows the output of the mixer with both an unsuppressed carrier (at the center of the major lobe) and poor code clock suppression (spikes at the null points). Both of these non-desireable effects are

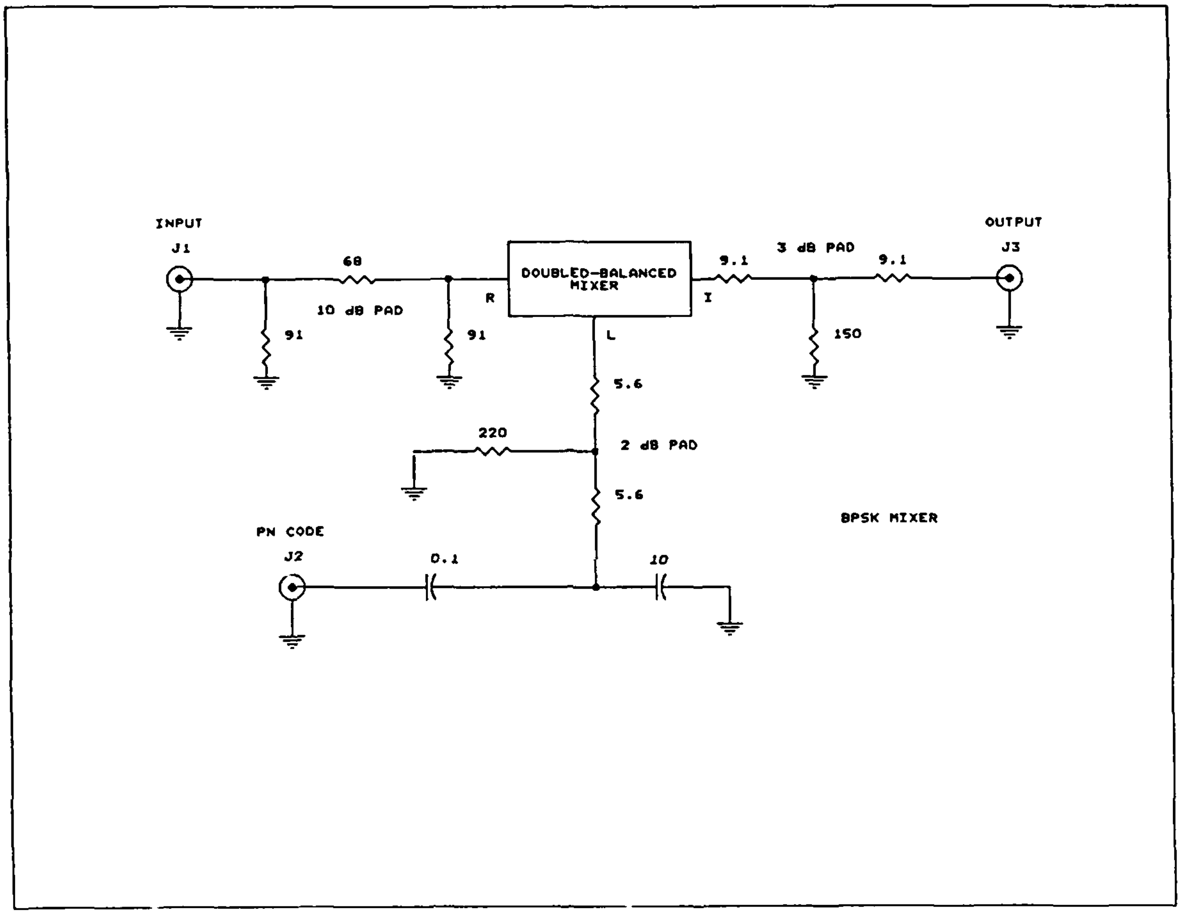


Figure 20. Transmitter DBM Circuit Diagram

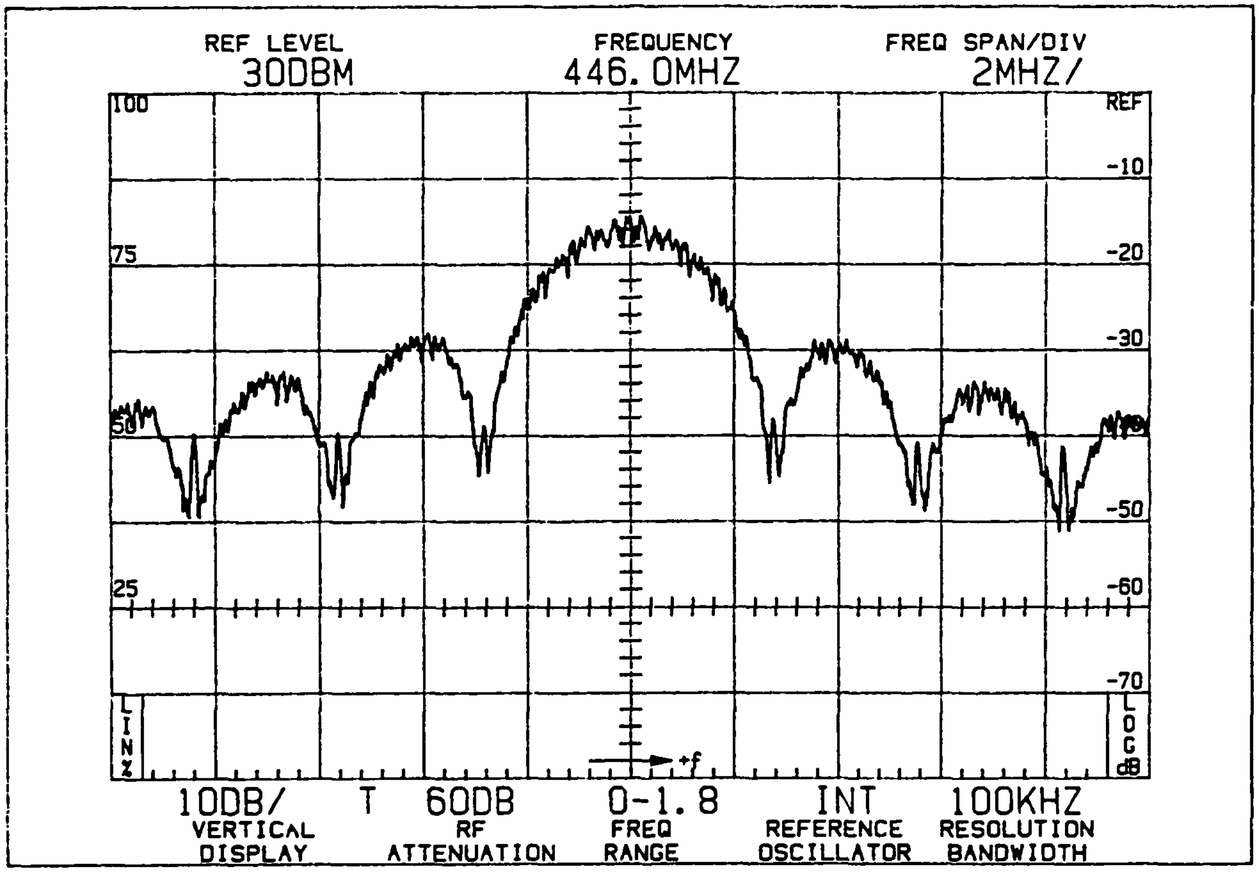


Figure 21. DBM Output showing Poor Carrier and Clock Suppression

attributed to non-symmetry in the code. Symmetry in the code satisfies the condition (7:109-125)

$$K_{+1} \int m(t)\ dt \quad = \quad K_{-1} \int m(t)\ dt. \qquad (16)$$

The signal envelope corresponding to a digital "1" must be equal to the signal envelope corresponding to a digital "0". There must be no dc component present in the signal. Code symmetry is difficult to provide in a practical system due to PN codes not being strictly random. Also, the rise and fall times associated with integrated circuits which generate these signals is usually not the same (7:115). The effect of not having adequate code-rate and carrier suppression is these signals may produce undesired narrowband signals in the receiver. Also, these spurious signals waste transmitter power and cause narrowband interference. In spread spectrum systems designed to reduce the probability of interception these signals are easily detected (7:117).

The Mini-Circuits, SBL-1, DBM is a level-7 mixer which means it requires a +7 dbm signal at the LO input port. This is the port where the PN code sequence is applied. Specifications for the SBL-1 are given in Table I (12:30).

Table I

Mini-Circuits, SBL-1, DBM Specifications

Frequency Range:

LO/RF	-	1-500 MHz
IF	-	DC - 500 MHz

Conversion Loss:

6.5 dB typical

Isolation:

LO-RF	-	40 dB typical
LO-IF	-	30 dB typical

Input Signal Level:

RF	-	up to + 1 dbm
LO	-	+7 dbm

(Source - 12: 30)

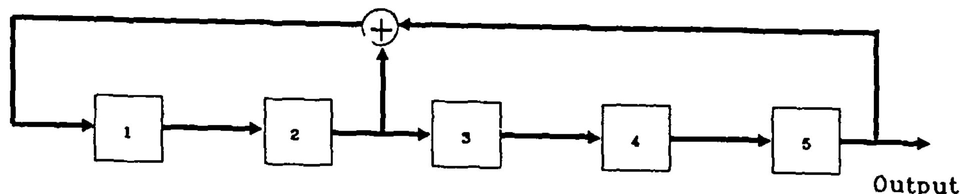
PN Code Generator

A design approach to building a spread spectrum communication system is to use a high rate random sequence for spreading the signal and another identical code at the receiver for despreading. This process is called the "stored reference" design approach because the random sequence must be duplicated at the receiver. It is not theoretically possible to use a "truly" random code in a stored reference system because randomness cannot be duplicated. For this and other reasons, pseudorandom or pseudonoise (PN) sequences were developed. PN sequences are digital waveforms which exhibit random-like properties but yet are deterministic. PN sequences are useful in communications, radar, ranging, and signal processing.

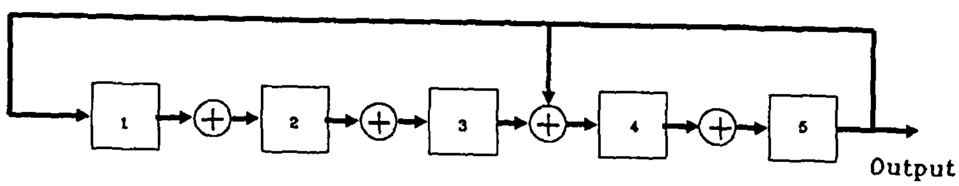
The PN code generator described is a major component of the DSSS system. The PN code generator is used to spread a narrowband frequency-modulated carrier to produce a direct-sequence spread spectrum signal. PN sequences are usually implemented using digital shift registers. In a shift register, the binary contents of each storage element are shifted to the next stage upon receipt of a clock pulse. The "initial fill" is the original contents of the register before the first clock pulse. Clearly, if no feedback was provided to the input, the contents of an n length shift register would empty after n clock pulses. A PN sequence is generated by tapping off the output of various stages of the shift register, adding these outputs, and feeding their Boolean sum back to the first stage. PN sequences generated using feedback from shift registers are a class of linear recursive sequences (LRS).

There are two configurations for implementing PN sequences (7:64-71). Figure 22(a) illustrates the configuration for a simple shift register generator (SSRG). Figure 22(b) illustrates the configuration for a modular shift register generator (MSRG). Both configurations can be made equivalent. However, the feedback taps are not the same for identical sequences. The MSRG configuration is the preferred design for the PN code generator used in the DSSS system. The MSRG technique reduces the time delays inherent in the feedback path to allow for a higher rate generator (7:66). To illustrate this, consider a multi-stage SSRG with several feedback taps. The delay consists of all the propagation delays in the path from the last stage to the first stage. Tnerefore, the feedback delay path sets the maximum useful speed of the sequence generator. The MSRG configuration delay is fixed and never greater than that of a single-tap sequence generator (7:66)

M-sequences. When the feedback taps from a shift register are properly selected, an LRS referred to as a "maximum sequence" or m-sequence is generated. This is the longest non-repeating sequence that can be generated by an n-stage shift register.



(a) Simple Shift Register Generator (SSRG) Configuration
for $X^5 + X^2 + 1$



(b) Equivalent Modular Shift Register Generator (MSRG)
for $X^5 + X^3 + 1$

Figure 22. Basic PN Sequence Generator Configurations

Table II lists the length of m-sequences from $n = 3$ to $n = 12$. The length of an m-sequence is computed as:

$$N = 2^n - 1 \quad \text{(bits)} \tag{17}$$

where, n is the number of shift register stages.

The time that a sequence runs until the bit pattern begins to repeat is known as the sequence period or code period. Table II tabulates sequence periods for m-sequences for a clock rate of 1 MHz.

For PN sequences to be useful, they must possess random properties but be deterministic. It is also desirable that these sequences are easily generated and difficult to reconstruct by those who do not have knowledge of the generating polynomial. This second feature improves the security aspect of the sequence. Fortunately, m-sequences meet these requirements very well.

Random properties. In a random binary sequence, the probability of a "1" will be the same as that of a "0". Therefore, on the average, there must be an equal number of "1"s and "0"s. This balance is nearly met in m-sequences because there is always one more "1" than "0"s in an m-sequence code period (7:59).

Table II

Code Sequence Periods for M-sequence Lengths (1 MHz)

Degree (n)	Length (bits)	Period (sec)
3	7	7×10^{-6}
4	15	1.5×10^{-5}
5	31	3.1×10^{-5}
6	63	6.3×10^{-5}
7	127	1.27×10^{-4}
8	255	2.55×10^{-4}
9	511	5.11×10^{-4}
10	1023	1.023×10^{-3}
11	2047	2.047×10^{-3}
12	4095	4.095×10^{-3}

To further illustrate the property of randomness, refer to Figure 23. This figure shows the power spectrum of a m-sequence pulse train. The power spectrum has discrete line elements that shape the sinc^2 function. The spectrum is discrete because the sequence is periodic. A "truly" random sequence would yield a continuous sinc^2 shape. The null points occur at the clock rate of the sequence. The line elements are spaced $1/NT_c$ apart, where N is the sequence length and T_c is the clock period. Therefore, the longer the sequence, the closer the line elements and the more continuous the power spectrum appears. Also, the higher the clock rate, the greater the spectrum is spread. Both N and T_c contribute toward providing random properties. As N approaches infinity, the power spectral density approaches that of white noise (7:98-104).

Polynomial notation. PN sequences are uniquely identified by an arithmetic polynomial. The polynomial identifies where the feedback taps are located. A sequence cannot be duplicated by more than one polynomial. The polynomial

$$f(x) = X^5 + X^2 + 1 \tag{18}$$

indicates feedback taps located at the 5th and 2nd stages are fed back to the first stage. This polynomial is implemented in Figure 22(a). For the MSRG and SSRG to be equivalent, the feedback taps are not the same. This is because the two

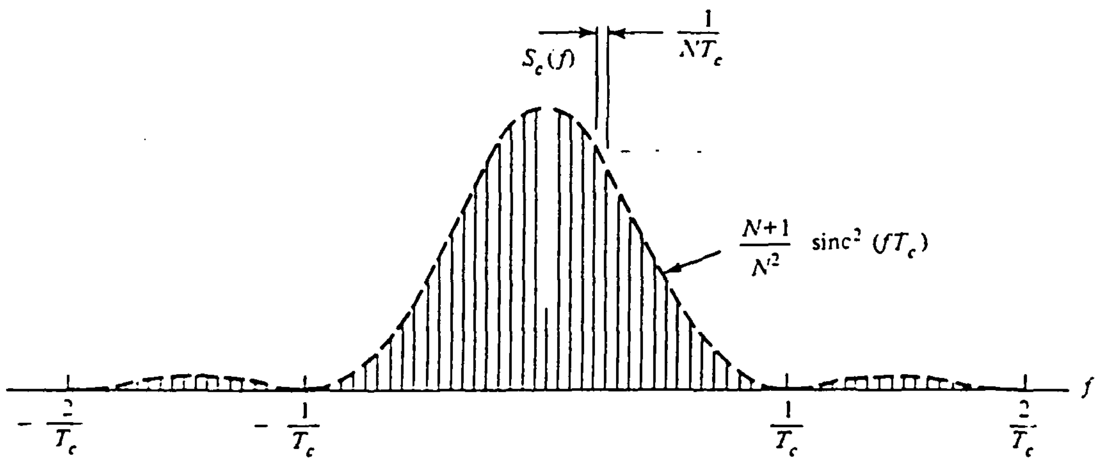


Figure 23. Power Spectrum of M-sequences with Chip Duration T_c and Period NT_c (8)

configurations will generate sequences that are "reciprocal" to each other if their taps are the same. A reciprocal sequence means that one sequence is in reverse order from the other sequence. To make the configurations equivalent, one polynomial must be the reciprocal to the other. The reciprocal polynomial, g(x), of an nth degree polynomial f(x) is

$$g(x) = x^n f(x^{-1}). \tag{19}$$

Therefore, the reciprocal polynomial of $x^5 + x^2 + 1$ is equal to $x^5 + x^3 + 1$.

Notice that the MSRG is Figure 22(b) has feedback taps at stages 5 and 3. This makes the PN sequences generated from the two configurations in Figure 22 equivalent. Table III lists additional polynomials that will yield m-sequence. Peterson and Weldon provides a complete listing of irreducible polynomials up to n = 34 from which m-sequences can be found (13:476-492).

<u>Autocorrelation.</u> Another extremely useful property of m-sequences is the autocorrelation function. The autocorrelation of a sequence is a numerical comparison of the sequence to a

Table III

Polynomials for M-sequences

Degree	* Octal	Polynomial
3	13 (15)	$X^3 + X + 1$
4	23 (31)	$X^4 + X + 1$
5	45 (51)	$X^5 + X^2 + 1$
	75 (57)	$X^5 + X^4 + X^3 + X^2 + 1$
	67 (73)	$X^5 + X^4 + X^2 + X + 1$
6	103 (141)	$X^6 + X + 1$
	147 (163)	$X^6 + X^5 + X^2 + X + 1$
	155 (133)	$X^6 + X^5 + X^3 + X^2 + 1$
7	** 203 (301)	$X^7 + X + 1$
	211 (221)	$X^7 + X^3 + 1$
	217 (361)	$X^7 + X^3 + X^2 + X + 1$
	235 (271)	$X^7 + X^4 + X^3 + X^2 + 1$
8	435 (561)	$X^8 + X^4 + X^3 + X^2 + 1$
	551 (455)	$X^8 + X^6 + X^5 + X^3 + 1$
	747 (717)	$X^8 + X^7 + X^6 + X^5 + X^2 + X + 1$
9	1021 (1041)	$X^9 + X^4 + 1$
	1131 (1151)	$X^9 + X^6 + X^4 + X^3 + 1$
	1461 (1063)	$X^9 + X^8 + X^5 + X^4 + 1$
10	2011 (2201)	$X^{10} + X^3 + 1$
	2415 (2605)	$X^{10} + X^8 + X^3 + X^2 + 1$
11	4005 (5001)	$X^{11} + X^2 + 1$
	4445 (5111)	$X^{11} + X^8 + X^5 + X^2 + 1$
	4215 (5421)	$X^{11} + X^7 + X^3 + X^2 + 1$
12	10123 (14501)	$X^{12} + X^6 + X^4 + X + 1$
	15647 (16273)	$X^{12} + X^{11} + X^9 + X^8 + X^7 + X^5 + X^2 + X + 1$
	16533 (15527)	$X^{12} + X^{11} + X^{10} + X^8 + X^6 + X^4 + X^3 + X + 1$

Source: 7:87

* SSRG (MSRG)

** Only FCC approved sequence in Amateur Radio Service shifted version of the same sequence. Mathematically, the autocorrelation function is expressed as (8:366)

$$R_c(t) = \frac{1}{T} \cdot \int_0^T C(t) \cdot C(t + \tau)\, dt \qquad (20)$$

where C(t) is a periodic sequence with period T and with values of ± 1.

This expression is plotted in Figure 24. When the sequence is not shifted (i.e. $t = 0 \bmod NT_c$), $R_c(t)$ peaks since the two sequences are identical and there is perfect agreement on a bit-by-bit comparison. However, when the sequence is shifted in time by any amount, $R_c(t)$ reduces to $-1/N$. This property is very important for synchronization of the stored reference code to the transmitted sequence (8:387-392).

<u>12-Stage generator design.</u> The actual PN code generator designed is shown in Figure 25. It is a 12-stage MSRG configuration. Switches and decoding logic are added to allow the generator to be programmable for any polynomial from degree-3 to degree-12. The PN code generator is designed such that setting of switches establishes the desired polynomial. Integrated circuits (ICs) U19, U20, and U21 determine the highest order term in the polynomial switch setting and disable the

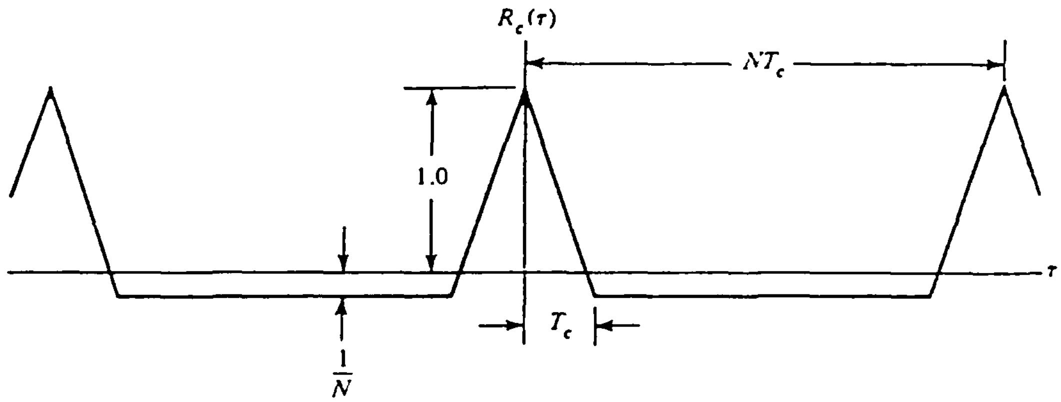


Figure 24. Autocorrelation Property of M-sequences (8:388)

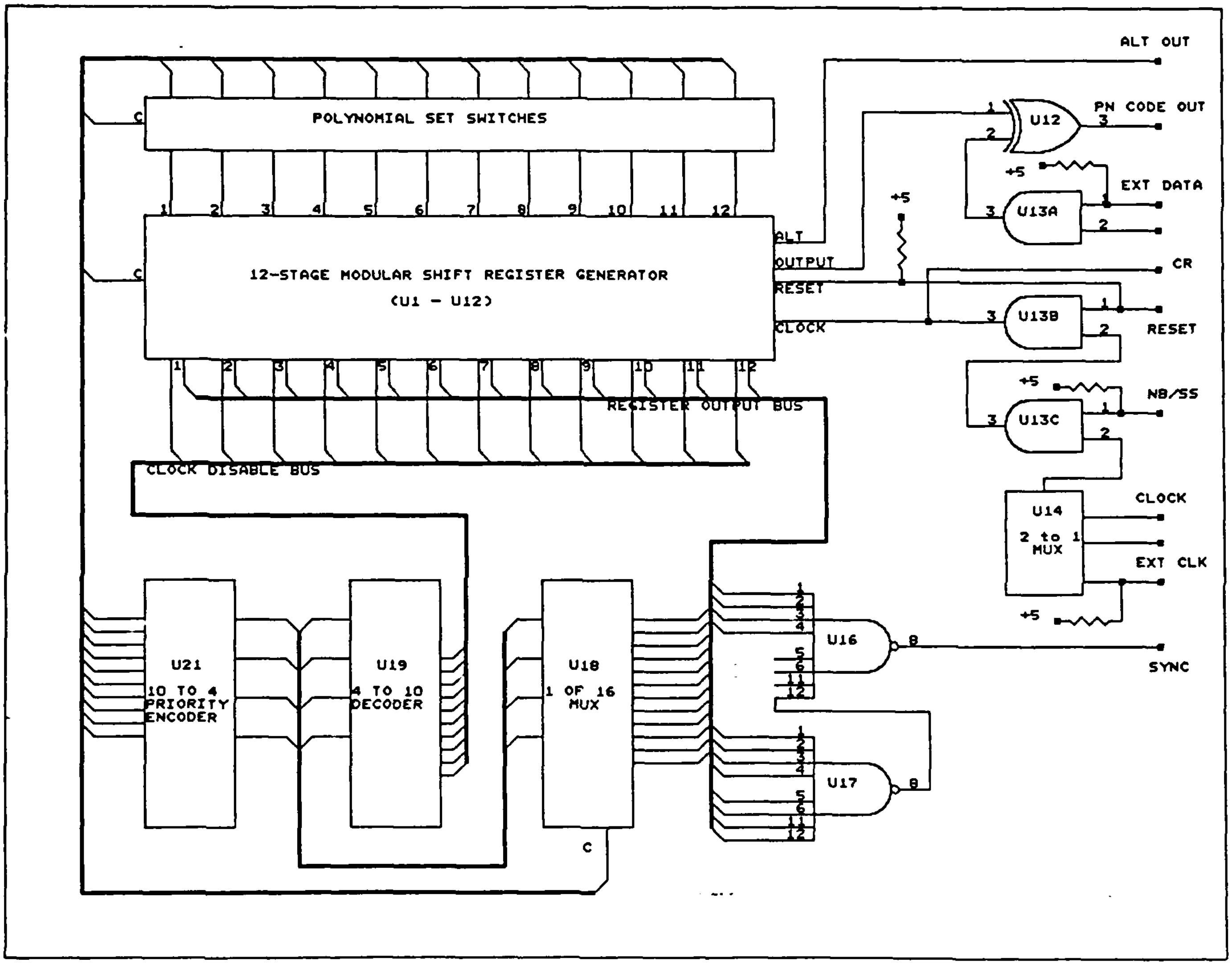


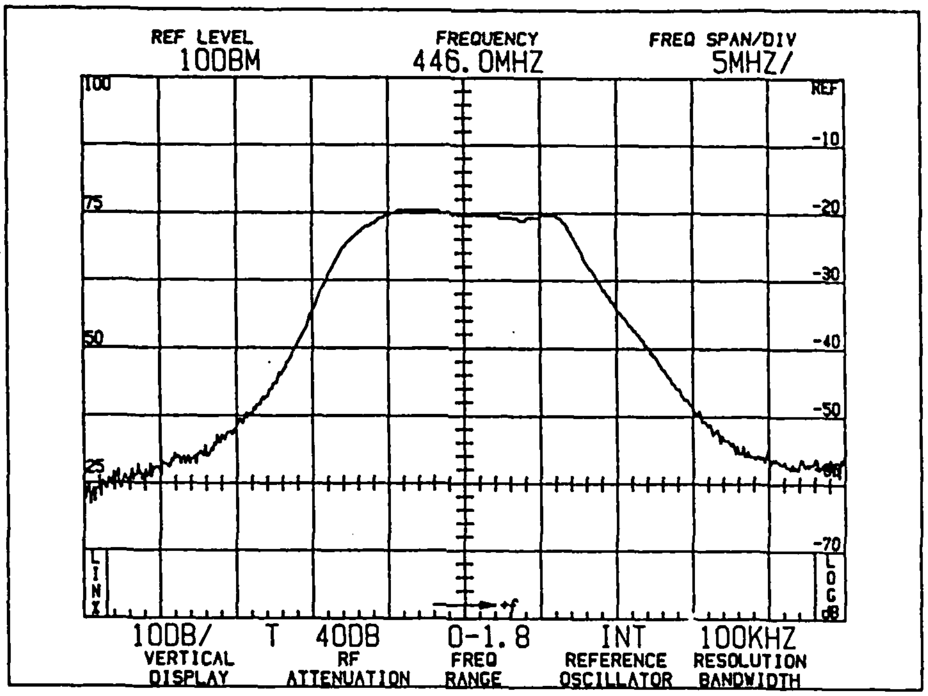
Figure 25. DSSS 12-Stage PN Sequence Generator

stages of the register not needed. Stages are disabled by inhibiting the clock signal at the next highest stage through gates U7, U8, or U9. Multiplexer IC U18 is used to complete the feedback path from the last stage and the feedback tap stages back to the first stage.

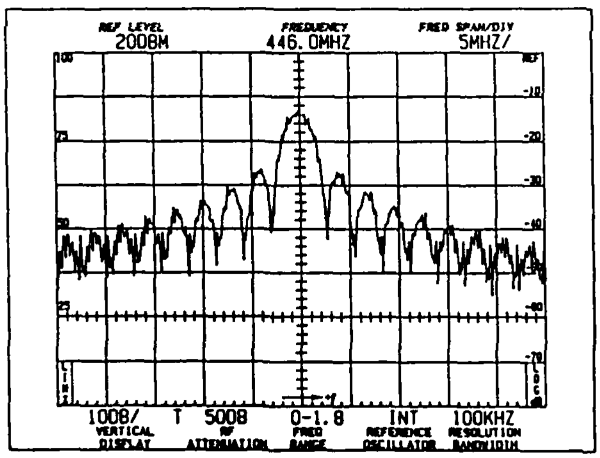
RF Amplifier / Filter

The RF Amplifier/Filter assembly consists of a Mini-Circuits, ZFL-1000H, preassembled broadband linear power amplifier, and a Hamtronics, HRF-432, preassembled helical resonator bandpass filter. The amplifier provides up to 100 mw (+20 dbm) output power with approximately 30 dB of gain. The ZFL-1000H has a rated noise figure of 5 db (14: 110).

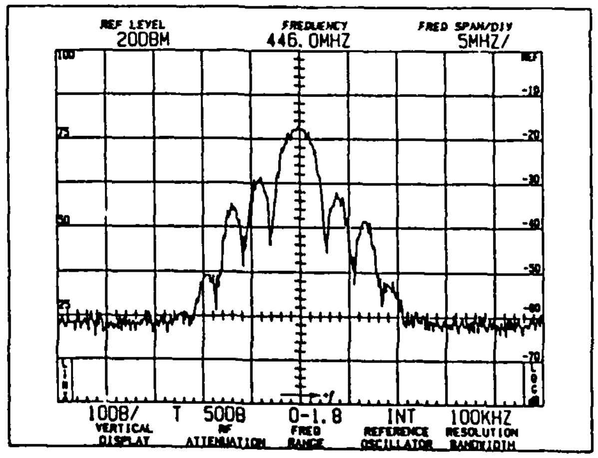
The HRF-432 helical filter has a response shown in Figure 26. A helical resonator is a modified cavity filter configuration often used at UHF. It consists of an inductor placed within a metal cavity. The HRF-432 is a compact 4-pole, cascaded, filter which provides good selectivity. In Figure 26, only 3 side-lobes remain after filtering. Although the first two side-lobes pass relatively unaffected, the third side-lobe is reduced by 10 db. Ideally, it is desireable to remove all side-lobes before amplification since 90 percent of the signal power



Filter Response Characteristic



Without Filter



With Filter

Figure 26. Hamtronics, HRF-432, Helical Resonator Filter Response Characteristic

is contained within the main lobe. Figure 27 shows what little affect the additional side-lobes contribute to the signal power (15:10.46, 7:23).

Antenna

The DSSS transmitter antenna is a Cushcraft, AR-450, Ringo. The AR-450 is a 1/2 wave, vertical antenna, that provides a wide bandwidth and low radiation angle. The AR-450 is omnidirectional providing 3.75 db gain over an isotropic source. The antenna provides approximately 20 MHz bandwidth with a radiation angle of 16 degrees. The overall antenna length is 1.4 feet (.43 m).

Special Design Features

External Clock (EXT CLK). An external clock input is provided for the DSSS transmitter PN code generator. The external clock input is enabled by the adjacent switch. An external clock is provided to add flexibility to the PN code generator. Using a clock rate other than 2.7875 MHz would not be compatible with the DSSS receiver because of the constraint imposed by the synchronous oscillator used for receiver synchronization. The external clock feature, however,

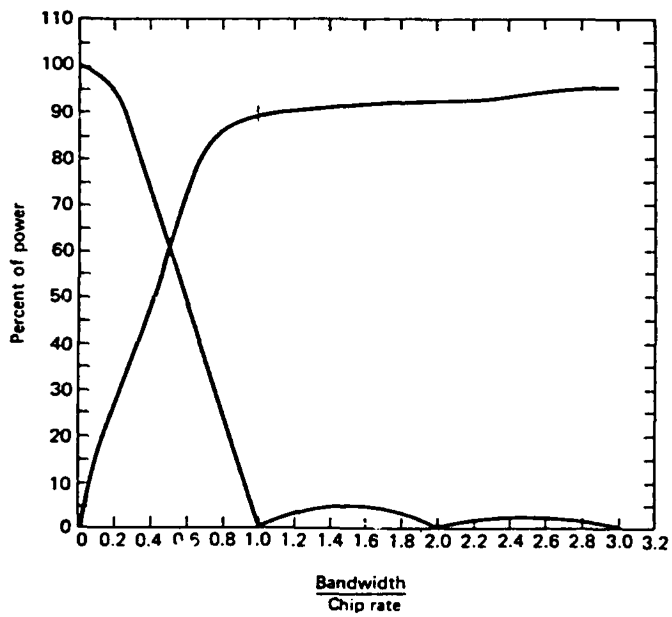


Figure 27. Power Distribution in $[\sin x/x]^2$ Spectrum (7:23)

is useful for demonstrating the effects of the DSSS signal spectra at various chip rates.

External Digital Data (EXT DATA). An external input is provided for combining digital data with the PN code sequence. The data and code are modulo-2 added when the adjacent switch is enabled. The use of external data is useful for experimentation with transmitting digital communications; however, the DSSS receiver cannot directly demodulate digital data transmitted in this manner.

Synchronization Pulse (SYNC). A pulse is output from the DSSS transmitter code generator at the PN code period rate. There are many uses for this output. It provides a means for determining the actual code length when the number of bits becomes too large to count or lock to on an oscilloscope (see Appendix A, Step 3). The synchronization pulse also provides a convenient means for observing transmitter and receiver synchronization. By inputting the SYNC outputs of both the DSSS transmitter and receiver into a dual-trace oscilloscope, synchronization can be observed when both pulses are identical in frequency and time epoch.

Chip Rate (CR). An external output from the DSSS transmitter PN code generator is provided for observing the chip rate waveform. This output is designed to input a frequency counter for observing the PN code clock rate.

Alternate PN Code Output (ALT OUT). The PN code generator is provided with two outputs. The primary output (PN CODE OUT) is taken from the first stage of the digital shift register. The ALT OUT is taken from the fourth stage of the digital shift register. Either output could be used by the DSSS system. Providing two outputs provides greater flexibility for experimentation into alternative ways to impose digital data onto the code. One technique called code shift keying (CSK) is accomplished by shifting the code sequence by n bits (in this case n = 3) in relation to the data stream. External circuitry would have to be developed to implement a CSK system fully.

Spread Spectrum Disable (NB/SS). A switch is provided that will disable the clock signal on the PN code generator. This will disable the spread spectrum modulation to the system and allow narrowband transmissions.

Receiver

Mathematical Representation

Refer again to Figure 4 for the DSSS system diagram. The received DSSS signal with no modulation and assuming no noise is repeated from equation (13)

$$s_i(t) = \text{BPF} [\; b_T(t) \; K \; A \cos (2\pi \, f_0 t \;] \qquad (21)$$

where, K now accounts for path losses.

The receiver amplifies $s_i(t)$ with the low-noise RF preamplifier and the signal is passed on to the DBM assembly. The receiver DBM assembly provides additional amplification before the mixer, and again, after the mixer. At the receiver DBM $s_{R1}(t)$ is multiplied by the PN code sequence $b_R(t)$. The output of the receiver DBM becomes

$$s_{R2}(t) = b_R(t) \; s_{R1}(t) \qquad (22)$$

$$= b_R(t) \; \text{BPF} [\; b_T(t) \; K_R \; A \cos (2\pi \, f_0 t \;] \qquad (23)$$

where, K_R now accounts for two stages of additional amplification.

Assuming ideal waveforms and perfect synchronization between $b_R(t)$ and $b_T(t)$

$$b_R(t) \quad b_T(t) = 1 \tag{24}$$

This results from the fact that when $b_R(t)$ and $b_T(t)$ are synchronized, they are aligned in both frequency and code epoch. The input to the FM narrowband receiver with no modulation is

$$s_{R2}(t) = K_R \ A \cos \ (2\pi \ f_0 t \ ) \tag{25}$$

where, K_R accounts for all system gains and losses up to the DBM assembly output. The receiver performs exactly the same with modulation present, except the modulation will be present on the carrier after multiplication by the synchronized $b_R(t)$. With arbitrary modulation, the input to the FM narrowband receiver is

$$s_{R2}(t) = K_R \ A \cos \ (2\pi \ f_0 t + k \int_{-\infty}^{t} m(t) \ dt) \tag{26}$$

where, all the terms, except K_R, are as defined in equation (4).

The narrowband FM receiver is a conventional FM receiver using a limiter/discriminator for detection. The signal processing beyond this point is standard and will not be discussed.

Antenna

The DSSS receiver antenna is the same type used in the transmitter. Refer to the transmitter section for antenna details.

RF Preamplifier

The RF preamplifier is a preassembled Hamtronics, LNG432, UHF, dual-gate gallium arsenide (GaAs) field-effect transistor (FET) device. Dual-gate devices are more stable than conventional triode GaAs FETs due to a lower feedback capacitance. The dual-gate GaAs FET device is also less subject to signal overload than bipolar transistor amplifiers. The LNG432 has a 1 dB compression point of +5 dbm The preamplifier provides a relatively flat +18 db response from 430 to 460 MHz. The noise figure is specified by the manufacturer as 0.8 db. Because of the low noise figure, the LNG432 used at the front-end effectively lowers the overall receiver noise figure. The RF preamplifier circuit diagram is shown in Figure 28 (16).

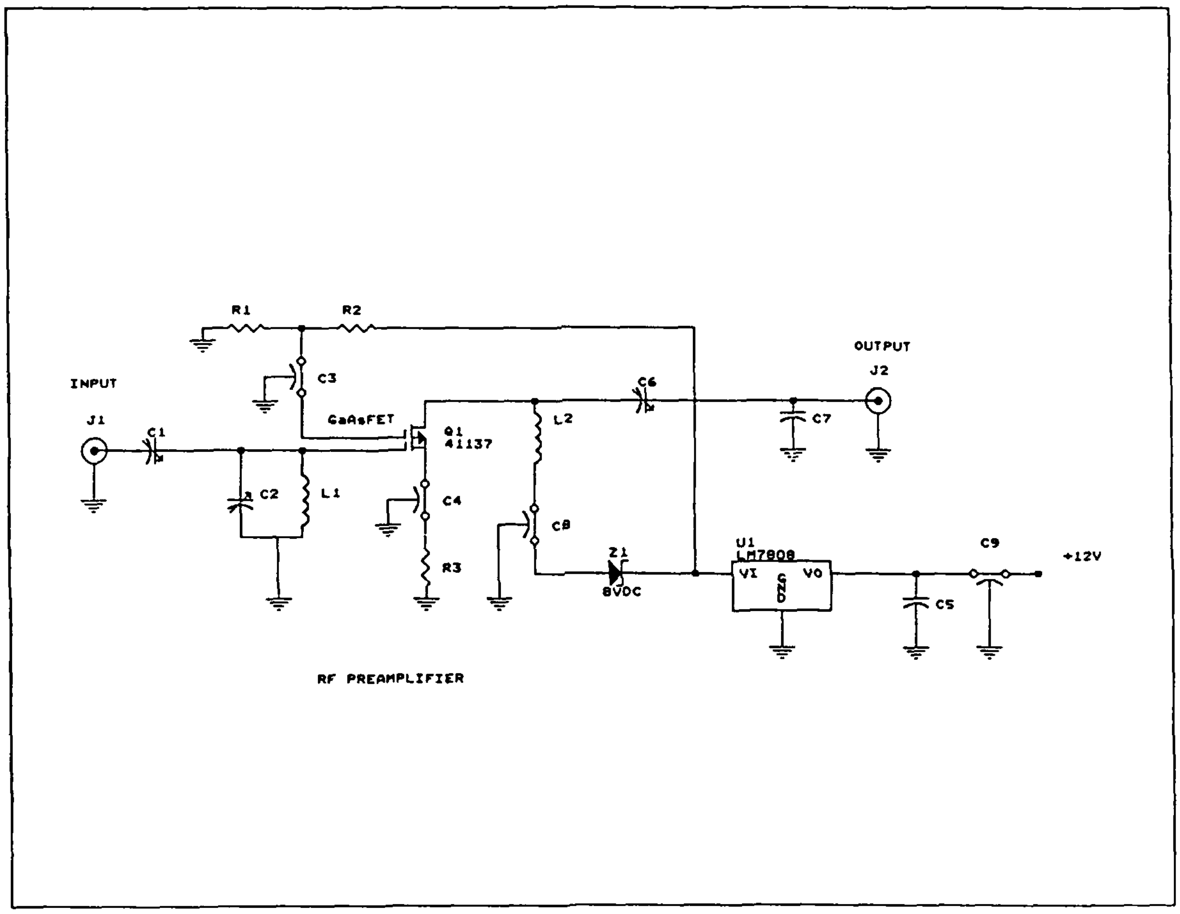


Figure 28. Hamtronics, LNG-432, Preamplifier Circuit Diagram (16)

Double-Balanced Mixer

The receiver DBM circuit is shown in Figure 29. The mixer assembly consists of a Mini-Circuits, SBL-1, DBM, an attenuator at each mixer port, a dc-blocking capacitor, and two Mini-Circuits, MAR-8, RF amplifiers. The receiver DBM is similar to the transmitter DBM except for the two MAR-8 RF amplifiers placed before and after the mixer. The receiver DBM also performs the mathematical function of multiplication. However, when the signal $s_{R1}(t)$, which contains the spreading waveform $b_T(t)$, is multiplied by the synchronized waveform $b_R(t)$, the effect is to remove $b_T(t)$ from $s_{R1}(t)$. Therefore, the DBM receives a spread waveform at the input (RF), a synchronized PN code at the LO port, and generates a despread narrowband signal at the output (IF) port. The output of the DBM is sent to the narrowband FM receiver for demodulation of the FM message and to the synchronous oscillator for achieving and maintaining synchronization.

The MAR-8 RF amplifiers are a class of silicon bipolar monolithic integrated circuits. The internal structure of the MAR-8 is a Darlington-connected pair of transistors with resistive feedback and a simple resistive biasing scheme (5:2-3). As can be seen from Figure 29, very few additional external components are required with these amplifiers. To design an

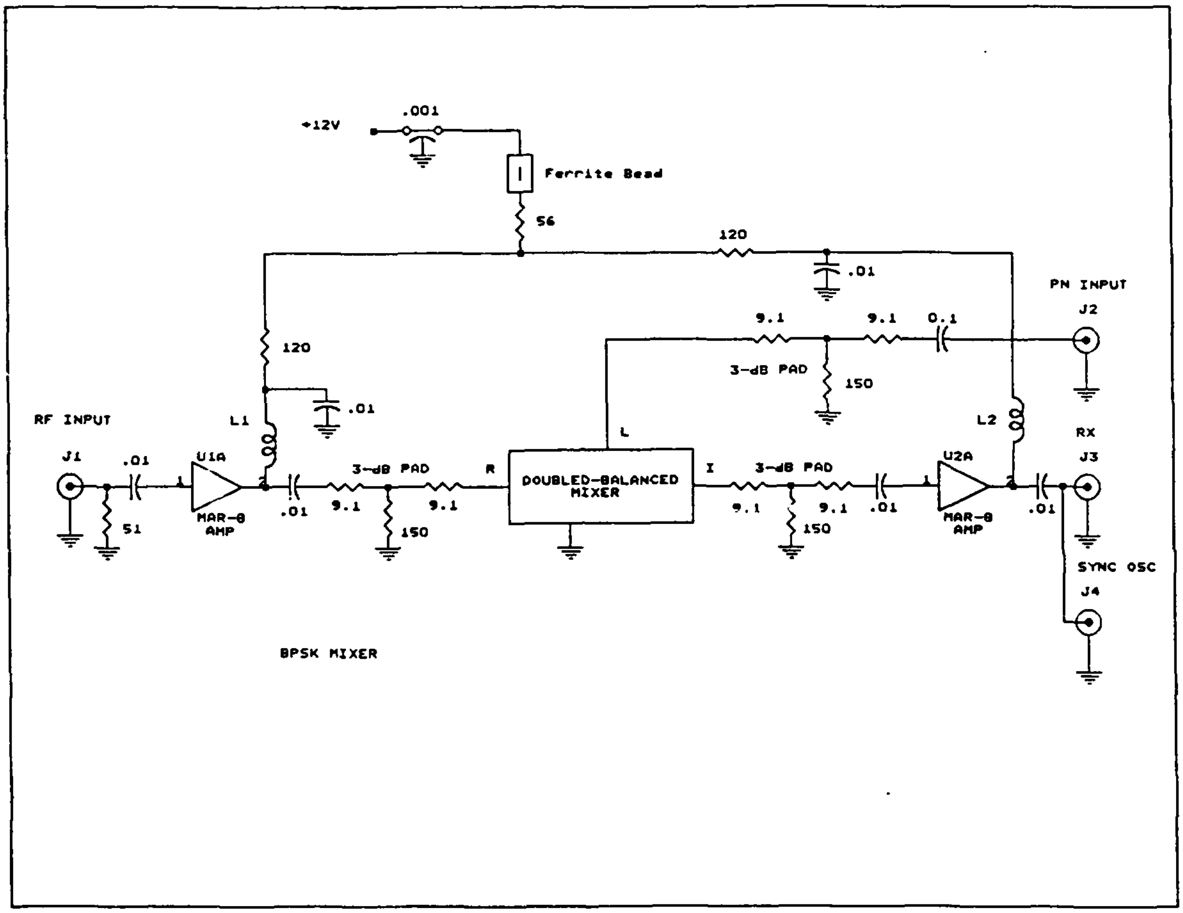


Figure 29. Receiver DBM Circuit Diagram

amplifier section, a 50 ohm microstripline, blocking capacitors, and a simple bias circuit is required.

In a microstrip structure, line impedance is determined by strip width, board dielectric material, and dielectric thickness. The MAR-8 amplifiers and the SBL-1 mixer, as well as the other assemblies of the DSSS systems, are prematched to operate in a 50 ohm system. Therefore, microstrip lines were designed for 50 ohms to achieve maximum device performance.

Epoxy-glass, G10, circuit board material was used which resulted in 0.1 in. width for 50 ohm microstrip (5:4). During board layout, care was taken to minimize all parasitics. The MAR-8 amplifiers were mounted on the etched side of the board to minimize the inductance of feed-through connections. Abrupt changes in transmission line width were avoided by tapering down to the amplifier lead widths. Ground planes were kept large and wire "feed throughs" were placed throughout the board as return paths for high frequency circulating currents. "Feed throughs" are holes in the board which connect the top and bottom ground planes (5:4-13).

Small gaps in the transmission lines were designed to allow for bridging by the 0.01 μf chip capacitors, which have relatively low parasitic inductance. Figure 13 is the best view of the strip-line construction. The section of this chapter that describes the transmitter DBM provides additional information regarding the SBL-1 mixer specifications and significant factors which apply to the receiver DBM.

PN Code Generator

The PN code generator used by the DSSS receiver is identical to the generator used by the transmitter. This is a necessary requirement as part of the "stored reference" design approach. Whereas the clock source for the transmitter PN code generator is derived from the FM exciter, the receiver PN code generator derives its clock source from the synchronous oscillator. Refer to the section in this chapter regarding the transmitter PN code generator for additional information which applies to the receiver generator as well.

Synchronous Oscillator

The problem of synchronization in direct sequence spread spectrum is that of aligning the receiver's locally generated PN code sequence with the spreading modulation superimposed on the incoming signal. This process is often accomplished in two steps. The first step, called "acquisition", consists of bringing the two spreading signals into coarse alignment. Once acquisition has occurred, the second step, called "tracking", takes over and continuously maintains fine alignment, usually by means of a feedback loop (17:6-7).

Specific synchronization requirements depend largely on the system application (17:6). Communication systems use spread spectrum modulation for a variety of reasons including anti-interference, anti-eavesdropping, power flux density reduction, low detectibility, multiple access, and ranging. Code lengths, bandwidth, and other system parameters are determined mostly from these system applications. The intended application must, therefore, be considered in determining a suitable synchronization technique. In the DSSS system described in this study, a practical synchronization process that is simple, reliable, and fast enough to support push-to-talk (PTT) operation was desired. Although necessary in military applications, a synchronization scheme that provides antijam properties was not necessary for the DSSS system.

Synchronous Oscillator Description. The synchronous oscillator is a synchronization network used for both acquisition and tracking. Uzunoglu and White (Ref. 4) were co-developers of the patented synchronous oscillator (U.S.Patents 4,274,067; 4,355,404; and 4,356,456). Fundamentally, the synchronous oscillator is a free-running oscillator in the absence of an externally applied signal. In the presence of a signal, the oscillator acquires and tracks the input waveform (4:1214-1225).

The synchronous oscillator's natural frequency is approximately 111.0 MHz. The external signal is received from the output of the DBM. The output of the oscillator is divided by 40 to create the clock signal. This locally generated clock signal, which at this point is only close in frequency to that of the transmitter's clock, is mixed with the 446 MHz spread spectrum signal, $s_{R1}(t)$, in the DBM. The free-running frequency of the synchronous oscillator will be at a rate either faster or slower than $b_T(t)$. The rate difference causes the receiver to "slide by" the transmitter sequence. Eventually, the two PN code sequences will be aligned to produce a correlation peak, as shown in Figure 24, at the mixer output. When correlation occurs, the output of the DBM collapses, or despreads, the spread spectrum signal into a narrowband signal similar to $s_{T1}(t)$. The mixer output at 446 MHz is instantaneously injected into the synchronous oscillator (1:17).

Providing the rate of $b_T(t)$ is not outside the tracking range of the synchronous oscillator, the oscillator will be "locked". Acquisition will have occurred and the synchronous oscillator will continue to track $s_{R1}(t)$. Under these conditions, synchronization will be achieved.

The synchronous oscillator operation is based upon the concept of injection-locked oscillators first introduced by Van der Pol (18:65) and later analyzed by Adler (19:351). When the synchronous oscillator is "locked" by the injection signal, the oscillator output is not equal to the injection signal, but frequency division by 4 occurs. The input to the mixer from equation (23), with no modulation, is

$$s_{R1}(t) = \mathrm{BPF}\ \{\ b_T(t)\ K\ A \cos\ (2\pi\ f_0 t)\ \} \qquad (27)$$

where,

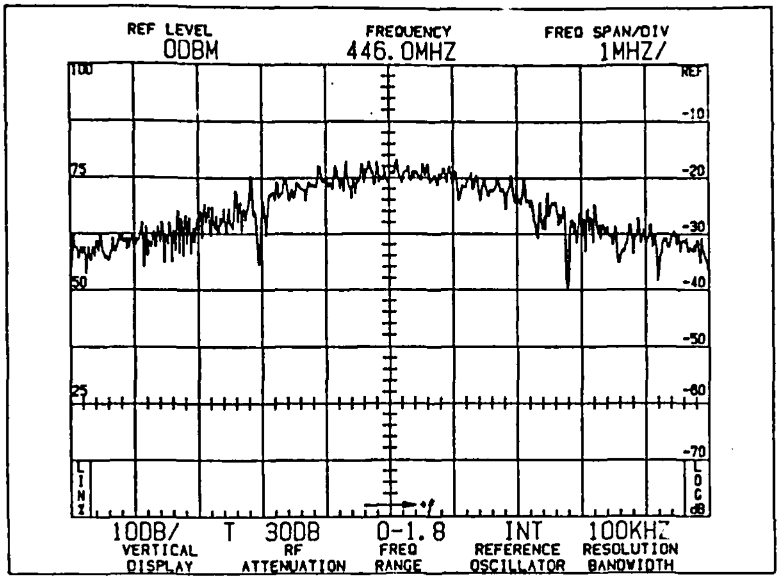
f_0 = carrier frequency (446 MHz)

K A = carrier amplitude

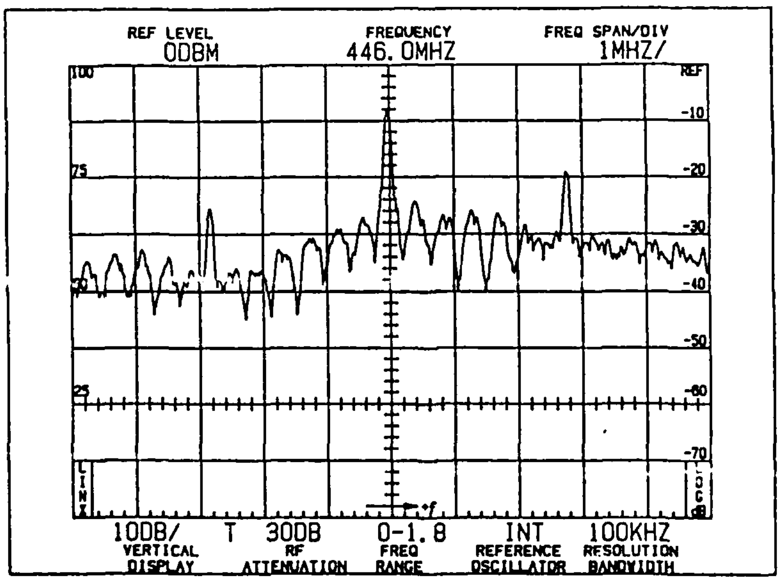
$b_t(t)$ = transmitter PN code sequence (2.7875 MHz chip rate).

The output of the mixer before $b_T(t)$ and $b_R(t)$ are synchronized (uncorrelated) is shown in Figure 30(a). When correlation occurs, even through $b_T(t)$ and $b_R(t)$ have not yet synchronized, the signal is injected into the synchronous oscillator. The oscillator will lock to precisely 111.5 MHz. This output is divided by 40 to produce the 2.7875 MHz chip rate which is identical to the transmitted rate. The DBM output becomes

$$s_{R2}(t) = K\ A \cos 2\pi\ f_0 t \qquad (28)$$



(a) Uncorrelated



(b) Correlated

Figure 30. DBM Output Showing Uncorrelated and Code Correlation Outputs

which is identical to $s_{R1}(t)$, equation (2), except for a change in amplitude. With modulation

$$s_{R2}(t) = K\, A \cos\left(2\pi f_0 t + k \int_{-\infty}^{t} m(t)\, dt \right) \tag{29}$$

which is identical to $s_{R1}(t)$, equation (4). The signal $s_{R2}(t)$ is passed on to the narrowband FM receiver for demodulation.

Figure 30(b) shows the spectrum of the DBM output when synchronization has occurred. The smaller peaks in the figure are at 2.7875 MHz intervals. These peaks represent products of the mixing operation due to the 2.7875 MHz chip rate. If the rate of $b_R(t)$ is outside the tracking range of the synchronous oscillator, the receiver operator must adjust the TUNE control until the rate is within the tracking range. When this has occurred, synchronization is achieved and readjustment is no longer necessary for several hours or more.

<u>Theory of Operation</u>. The synchronization oscillator circuit diagram is shown in Figure 31. The oscillator is a modified Colpitts oscillator. Modified in the sense that an active emitter load, Q1, is added. Capacitors C2 and C3 and inductor L2 form the frequency determining tank circuit. The "free running" oscillator frequency is given by:

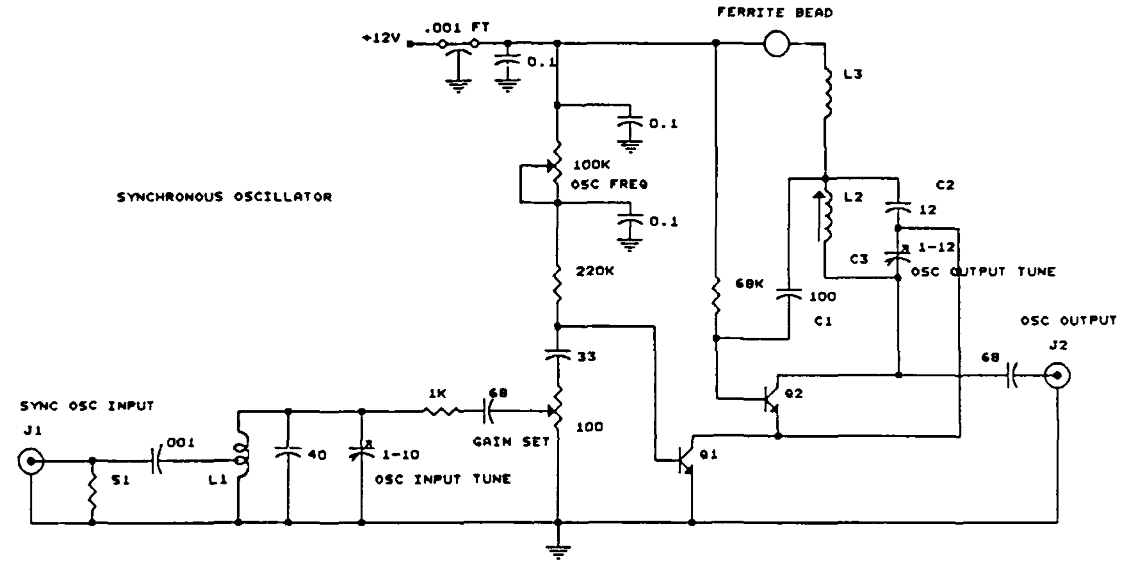


Figure 31. Synchronous Oscillator Circuit Diagram

$$f_r = \frac{1}{2\pi} \cdot \left\{ \frac{C2 + C3}{L2 \quad C2 \quad C3} \right\}^{1/2} \tag{30}$$

(4:1215)

With the component values, as specified in Figure 31 and L2 slug-tuned to about 0.4 μh, the free-running frequency is near 111.5 MHz.

The oscillator has two positive feedback paths, one from the point between C2 and C3 back to the emitter of Q2, and the other through C1 to the base of Q2. C1 is large and represents a very low impedance at the operating frequency. Q1 acts as a dynamic emitter resistor to Q2. Transistor Q2 operates in class C and the conduction angle is very small. Each time conduction occurs in Q2, a voltage develops across Q1. Q1 amplifies the input signal and injects current into Q2 during the brief conduction time. Conduction in Q2 is similar to the opening of a very brief "time window" during which synchronization to the input signal occurs. In the event of a temporary absence of sync pulses, the tank (functioning as a flywheel) continues to produce a sinusoid at a frequency close to one-fourth of the input frequency (20:516-517).

In operation, the synchronization oscillator is a non-linear oscillator with high internal gain and a saturated output amplitude in the tracking range. The injected input signal modulates the phase but does not disturb the output amplitude of the oscillator. It is the transconductance of Q1 that provides the injection into Q2, while the transconductance of Q2 overcomes circuit losses (4:1215). In general, these transconductances are non-linear. Therefore, the differential equation representing the output in terms of the input is highly non-linear. Only approximate linear solutions have been developed (20:517, 21:93). It is beyond the scope of this research effort to attempt to develop approximate linear transfer functions in the regions of operation for the synchronous oscillator.

FM Receiver

The Hamtronics, R451, is a commercial quality, single channel, UHF FM receiver. The R451 features a GaAs FET RF amplifier and first mixer for very good sensitivity. It also contains an 8-pole crystal filter and a ceramic 2nd IF filter for superior IF selectivity. The frequency of operation is determined by a 32 pf, parallel resonant crystal (22). The crystal operates in fundamental mode according to the following expression (22)

$$\text{Crystal Frequency (MHz)} = (f_0 - 10.7) / 27 \qquad (31)$$

For f_0 = 446.00 MHz, the crystal frequency is 16.122 MHz. The receiver can provide ample audio to an 8 ohm loudspeaker; or it can drive higher impedances 1K to 10K for external devices. The RF input is matched to a 50 ohm impedance.

The R451 schematic diagram is shown in Figure 32. Q1 is a dual-gate GaAs FET which offers low noise, good stability, and improved overload rejection of strong signals. Q3, Q4, and Q6 comprise the local oscillator. The mixer output produces a 10.7 MHz 1st IF. U2 is a Motorola MC-3359P, IF amplifier IC which performs a second frequency conversion to 455 kHz, IF amplification, limiting, and demodulation. The demodulator is an FM discriminator designed for narrowband FM at $\pm$ 5 kHz frequency deviation (22).

The MC-3359P provides for automatic frequency control (AFC) and a squelch control (Q5). Audio is passed to U1, a National LM-380N amplifier IC. L9 to L11 comprise the 3-section helical resonator RF filter before the mixer. FL1 to FL4 comprise the 8-pole, 10.7 MHz IF, crystal filter. The 455 kHz 2nd IF ceramic filter is FL5 (22).

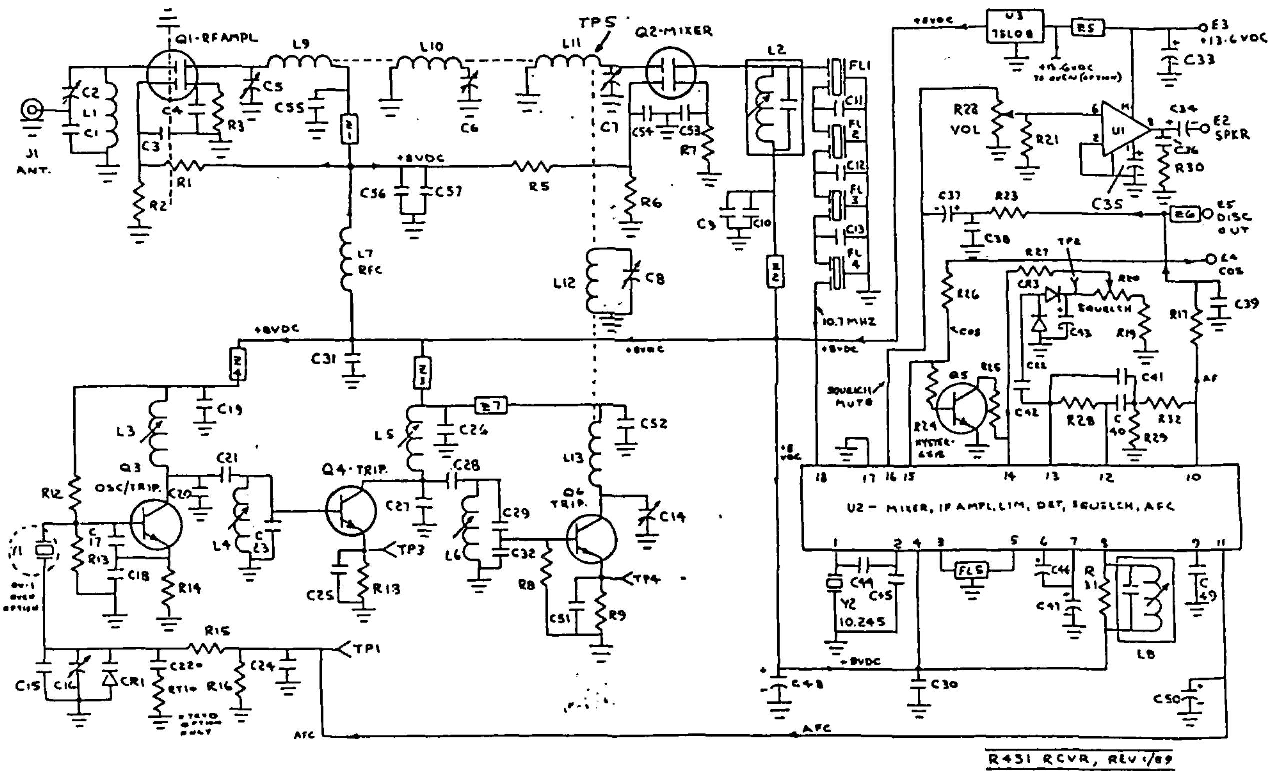


Figure 32. Hamtronics, R451, Narrowband FM Receiver Circuit Diagram (22)

Special Design Features

Most of the receiver special design features have already been described in the transmitter section of this chapter. The following are the features which are different than those of the transmitter:

External Digital Data (EXT DATA). This feature is not available on the DSSS receiver. This feature relates to imparting data which is not a receiver function. Since the same PN code generator is used in both the transmitter and receiver, an EXT DATA input is available on the generator circuit board. However, EXT DATA is not brought out to the receiver front panel.

Discriminator (DISCRIM). An external output from the narrowband FM receiver discriminator is provided. One possible application of this output is to drive a subaudible tone decoder for selective calling. There are many possibilities for this output using additional external circuitry.

IF. An external output from the receiver mixer output is provided at the front panel. This output at 446 MHz, is not a true IF since the basic receiver does not down convert the received signal to an intermediate frequency (IF), except in the narrowband FM receiver. It is possible to couple the 10.7 MHz IF from the narrowband FM receiver, but this has not be done. This feature would make it possible to process the transmission of digital data external to the basic DSSS receiver. External circuitry would be necessary to coherently recover the BPSK modulation resulting from digitally transmitted data.

V. Performance Testing and Results

This chapter provides the results of the DSSS system tests and evaluation. Tests of synchronization time, processing gain, and bit-error rate were conducted in the laboratory. Tests of the ease of synchronization and communications range were field tested. The effects of interference which were intended to be field tested were conducted in the laboratory. This change was necessary because the lack of receiver sensitivity limited the range of communication for the DSSS system. The methods used for determining each of these parameters, along with the summarized data are included.

Synchronization

Synchronization time was measured with instrumentation configured as shown in Figure 33. A received signal level of 0 dBm was used to ensure a large SNR. The FSK demodulator was adjusted to keep the HP5326A Interval Timer enabled until it sensed an audio tone of approximately 2 kHz from the receiver. When the DSSS transmitter was keyed, the SYNC pulse was generated from the PN code generator at the code period rate of $1/T_N$. The SYNC pulse cannot be generated until the transmitter is keyed. At the first SYNC pulse, the HP5326A Interval Timer is enabled.

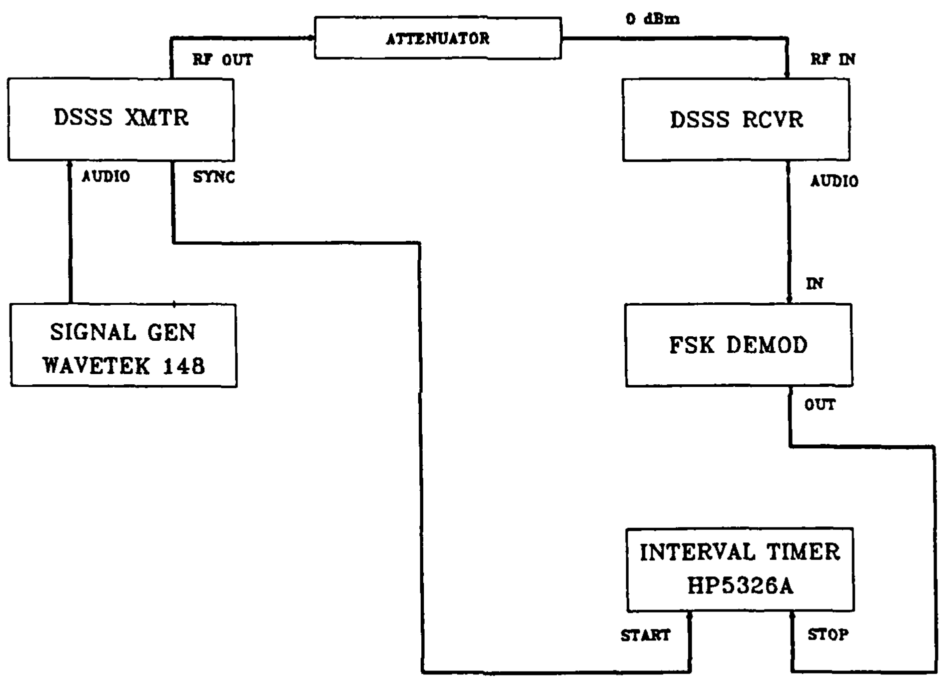


Figure 33. Equipment Block Diagram for Synchronization Time Measurement

The HP5326A is disabled when the 2 kHz tone is received by the FSK demodulator. The time difference between the start and stop signals is the total synchronization time.

The results of the synchronization time trials are tabulated in Table IV. The additional propagation times resulting from the FSK demodulator, the FM narrowband receiver, and the propagation path are small by comparison and are neglected. In fact, these delays are somewhat offset by the fact that the first SYNC start pulse is actually delayed by one code period equal to 46.04 μs.

Processing Gain

The theoretical value of the processing gain is compared to a measured value. By definition, processing gain G_p is

$$G_p = B_{ss} / B_D \tag{32}$$

where,

B_{ss} = bandwidth of the DSSS signal in Hz

B_D = minimum bandwidth necessary to send the information in Hz.

A null-to-null bandwidth is assumed for the spread spectrum signal and a bounded power spectral density bandwidth (4 kHz) is

Table IV

Synchronization Time Measurement Data

Trial No.	Synchronization Time (ms)
1	164
2	164
3	160
4	164
5	164
6	164
7	166
8	168
9	165
10	163
11	164
12	161
13	165
14	165
	164.1 Average

assumed for the analog voice channel. The measured G_p is determined by the expression

$$G_p = \text{Output SNR} / \text{Input SNR} . \qquad (33)$$

The measured processing gain amounts to expressing G_p as the SNR in the DSSS signal divided by the SNR in the narrowband signal. Table V lists the signal and noise levels, as measured from the spectrum analyzer, and their corresponding SNR for both input and output. Figures 34 and 35 are the spectrum analyzer plots from which these measurements were taken. The theoretical and measured processing gains differ by only 4.4 dB. This is reasonable allowing for conversion losses and bandwidth approximations.

Bit-Error Rate

FSK at 300 bps was measured with instrumentation configured as shown in Figure 36. The DSSS transmitter and receiver were connected directly through a stepped attenuator from 0 to 110 dB in 1 dB increments. The SYNC outputs were connected to the HP1746A oscilloscope to observe that the transmitter and receiver were synchronized. The HP1746A was set to the dual trace (chop) mode to trigger on the transmitter SYNC pulse. The receiver synchronous oscillator TUNE control was adjusted, when needed, to

Table V

Processing Gain Measurement Data

Input

Signal level	=	-43 dBm
Noise level	=	-83 dBm
SNR	=	40 dB

Output

Signal level	=	-8 dBm
Noise level	=	-75 dBm
SNR	=	67 dB

Measured Processing Gain

G_p (dB) = 67 dB - 40 db = $\boxed{27.0 \text{ dB}}$

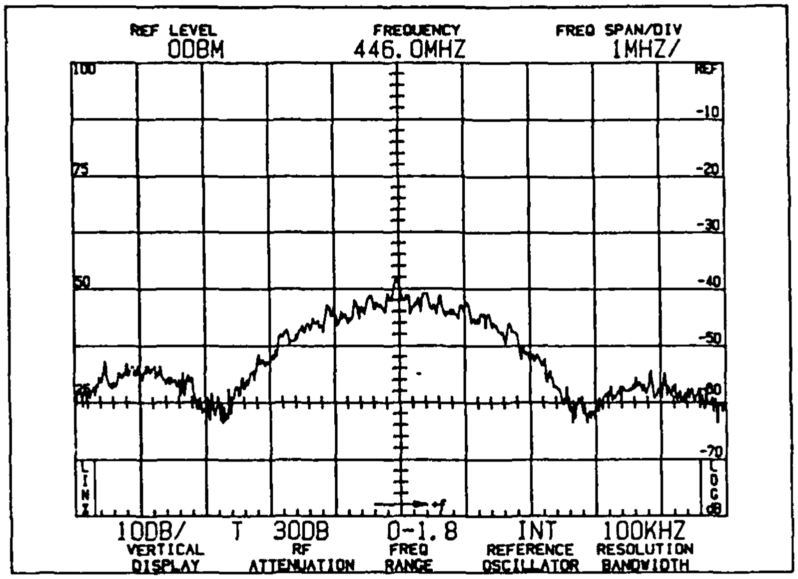
Theoretical Processing Gain

DSSS Bandwidth (null-to-null) = 5.575 MHz

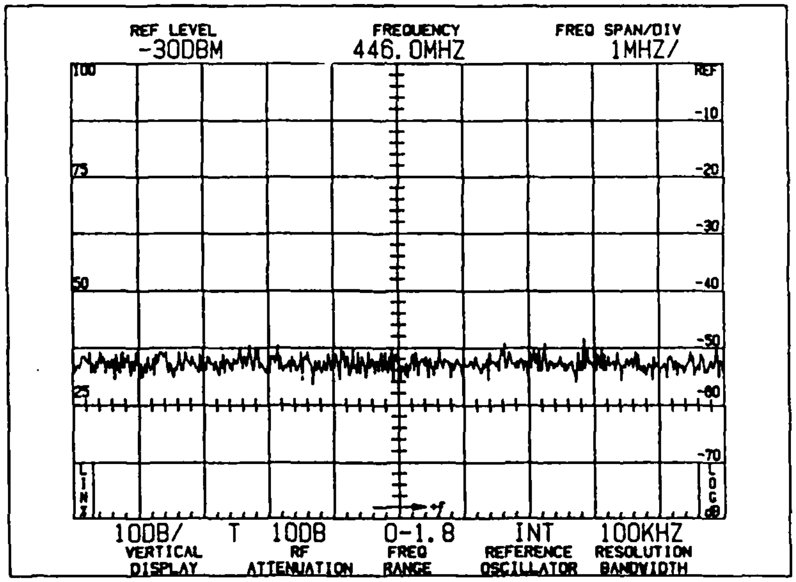
Baseband Bandwidth = 4 Khz

G_p (db) = 10 log [5.575 MHz / 4 kHz]

= $\boxed{31.4 \text{ dB}}$

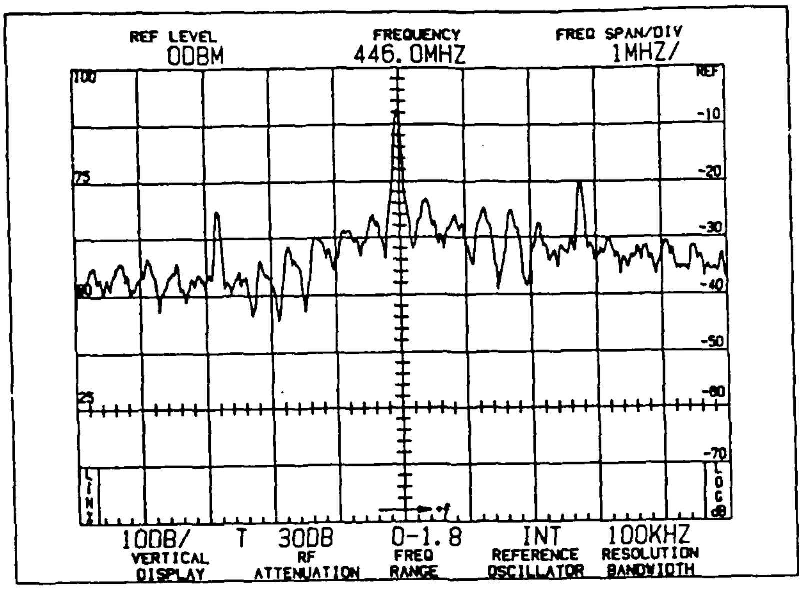


(a) Signal Power

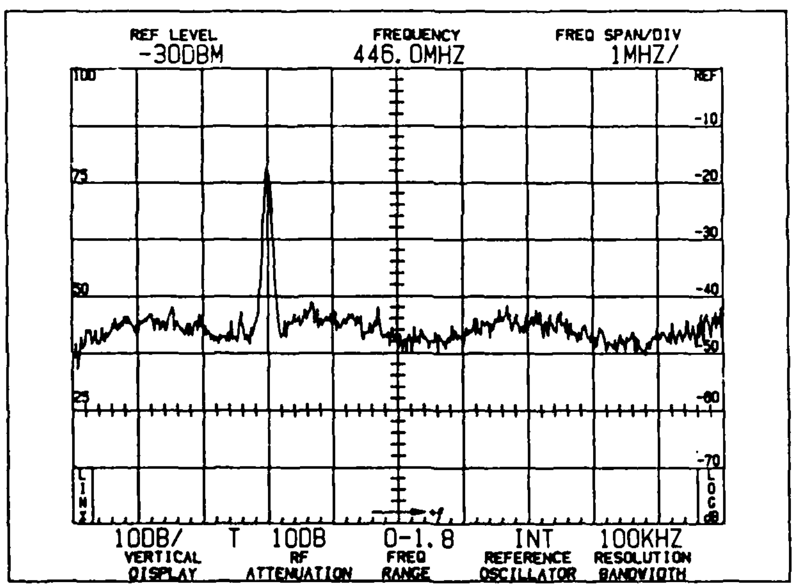


(b) Noise Power

Figure 34. Input SNR Spectrum Analyzer Plot



(a) Signal Power



(b) Noise Power

Figure 35. Output SNR Spectrum Analyzer Plot

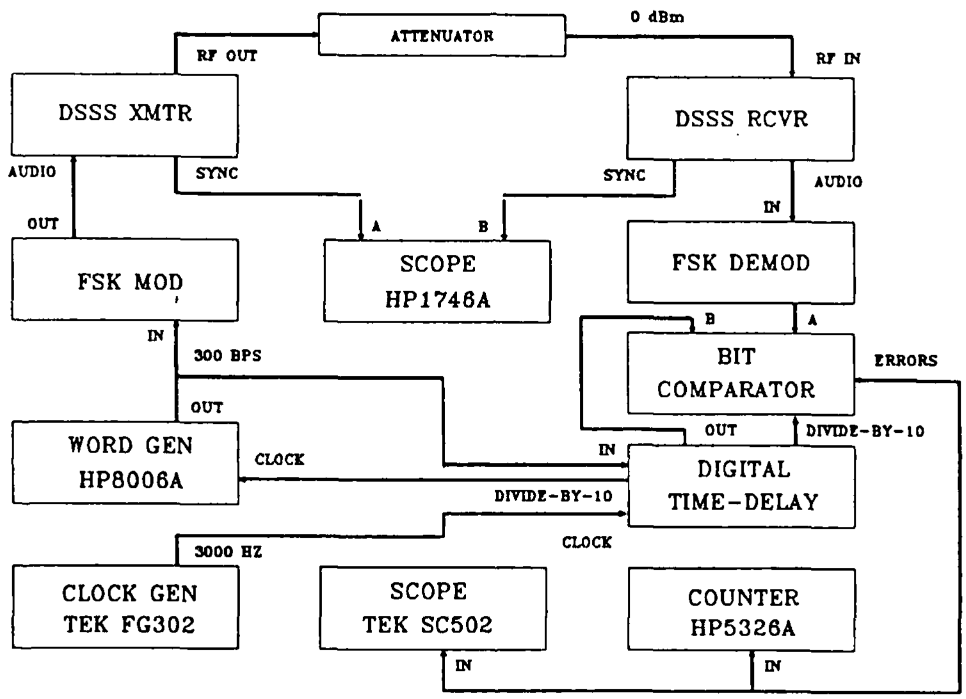


Figure 36. Equipment Block Diagram for Bit-Error Rate Measurement

maintain code rate and epoch alignment with the transmitter PN code. The FSK modulator was configured to output 300 bps FSK with 2025 Hz and 2225 Hz tones. The simulated data was generated by an HP8006A word generator.

Test data consisted of a PN sequence of length $2^{16} - 1$ bits in order to assure randomness over the measurement interval. Errors were detected by a bit comparator device comprised of a clocked exclusive-OR gate. If the bits at port A and B are alike, then no error was produced. If the bits were different, then one pulse was generated. The total number of errors counted by the HP5326A Timer-Counter over an interval of usually 10 seconds (3000 bits) was used to determine the bit-error rate. The TEK SC502 oscilloscope was used to observe the error waveform to insure proper error counting.

The input waveforms to the bit comparator device must be aligned in time to within approximately 10-20% of a bit period. However, a time delay of greater than 1 ms was present between the waveform at input A (transmitted waveform) and the waveform at input B (received waveform). This caused excessive errors to be falsely recorded by the counter. To correct this problem, a digital time-delay device was inserted in the measurement system.

The digital time-delay device delayed the transmitted waveform by an adjusted amount so that the waveforms were aligned. For the digital time delay to work properly, it was necessary to clock the device at 3000 Hz, 10 times the 300 bps rate. Two clock signals were output from the digital time-delay device at a divide-by-10 rate to maintain the 300 bps rate.

The bit-error rate measurement data is recorded in Table VI. These data are the average values after approximately 10 trials at each signal level. The DSSS receiver was having difficulty maintaining synchronization at signal levels below approximately -40 dBm. The error rate was recorded only during periods of synchronization.

The probability-of-error versus SNR are plotted in Figure 37. A plot of theoretical, non-coherent, binary FSK is also shown in Figure 37. Note that the theoretical non-coherent FSK curve is 3 dB to the left of the E_b / N_0 curve (i.e. E_b / N_0 = 2 SNR). The extreme difference between the measured bit-error rate and the theoretical value is attributed to poor receiver sensitivity.

Field Testing

DSSS system field tests were conducted in the park adjacent to the AFIT engineering building, at Wright-Patterson Air Force Base. Figure 38 shows the equipment configuration for the

Table VI

Bit-Error Rate Measurement Data

Attenuation	SNR	BER
0	83	0
-10	73	0
-20	63	0
-30	53	0
-35	48	0
-36	47	3.6×10^{-4}
-37	46	9.0×10^{-3}
-38	45	1.2×10^{-2}
-39	44	2.0×10^{-2}
-40	43	1.1×10^{-1}
-41	42	2.2×10^{-1}
-42	41	2.8×10^{-1}
-43	40	2.9×10^{-1}
-44	39	3.5×10^{-1}
-45	38	5.1×10^{-1}
-50	33	5.0×10^{-1}

Input Signal Level	= 0 dBm
Noise	= -83 dbm
Data Rate	= 300 bps

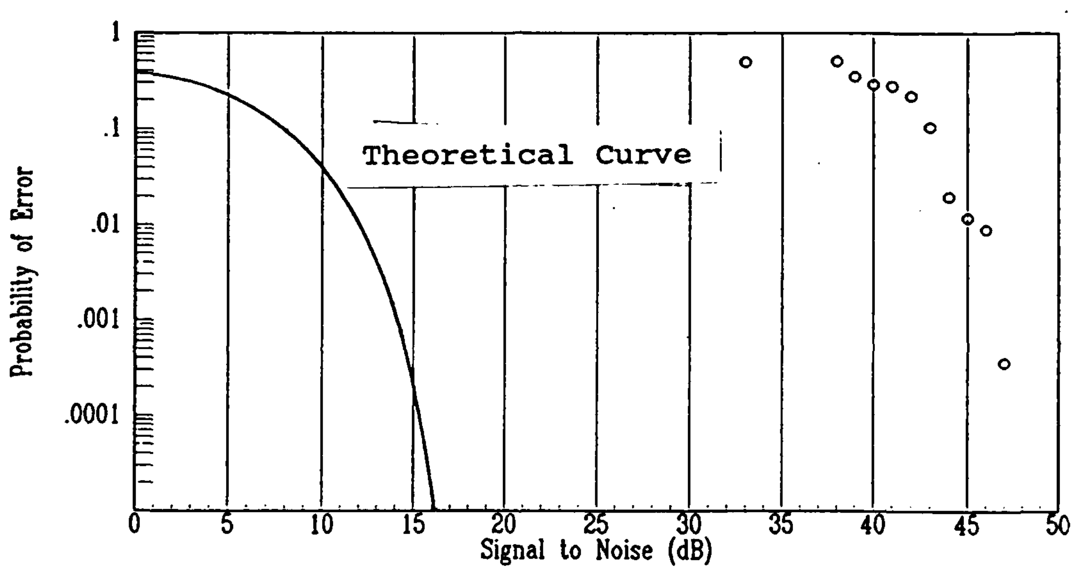


Figure 37. Bit-Error Rate versus Signal-to-Noise Ratio

transmission of a 1 kHz test tone. Figure 39 shows the equipment configuration for the transmission of 300 bps FSK. The TEK 494P spectrum analyzer was initially connected to the mixer output to confirm DSSS system synchronization. Before testing, station identification was given by narrowband transmission in accordance with FCC Rules and Regulation.

Before field tests were conducted, a receiver sensitivity test was performed in the laboratory. This test determined the maximum path loss that could be tolerated before the DSSS system lost synchronization. Maximum path loss was measured by connecting the DSSS transmitter, through the stepped attenuator, into the DSSS receiver. Attenuation was added until the receiver lost synchronization. Problems with synchronization began at 40 dB of attenuation. Synchronization was unacceptable at 45 dB and a complete loss of synchronization occurred at 50 dB.

Figure 40 is a plot of the expression for free-space path loss (23:202)

$$L\ (\mathrm{dB}) = 10 \log\ (4 \cdot d\ /\ \lambda\ )^2 \qquad (34)$$

where,

d = distance in meters

λ = frequency in wavelength

$\lambda = c\ /\ f =\ 0.673$ m (at 446 MHz).

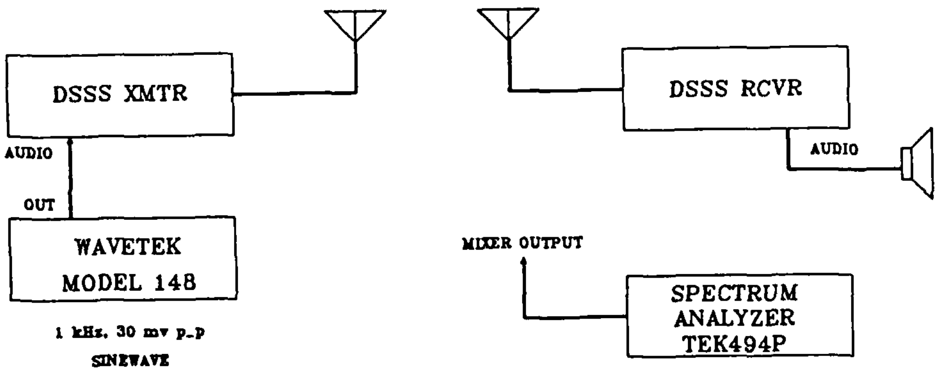


Figure 38. Equipment Block Diagram for Field Tests - Test Tone

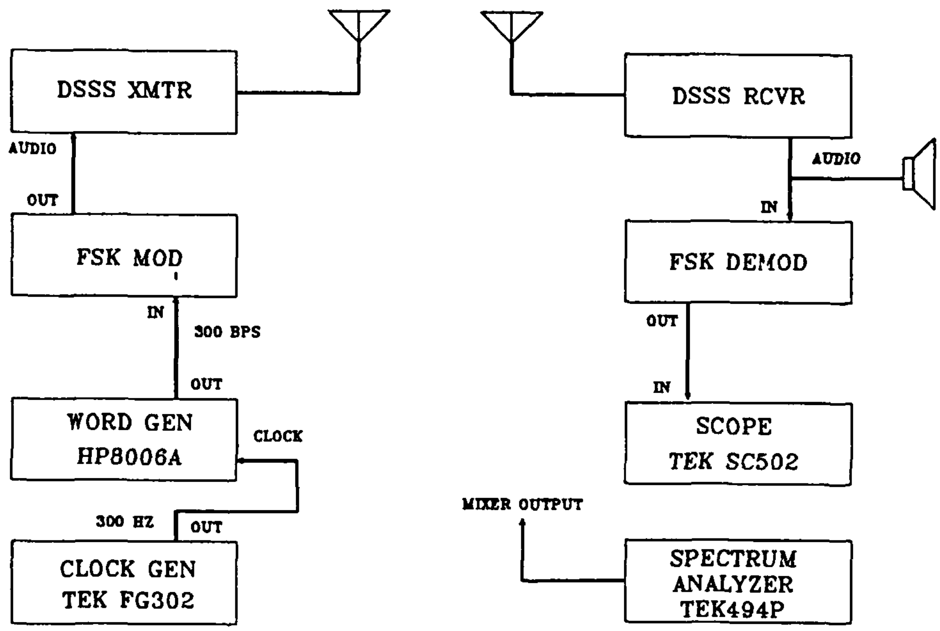


Figure 39. Equipment Block Diagram for Field Tests - FSK

From Figure 40, a predicted range of only 5 to 10 meters was expected. This is due to the limited transmitter power and poor receiver sensitivity. The range prediction was verified during field testing. Synchronization was not achieved until the transmitter and receiver antennas were approximately 1 meter apart; but remained in synchronization at a distance of approximately 5 meters.

Effects of Interference

The effect of co-channel, narrowband, interference on the performance of the DSSS system was originally intended to be evaluated during field testing. It was decided that this test could be more appropriately performed in the laboratory because of the limited range over which the system could operate. The laboratory interference tests were not an exhaustive test of the effects of interference on the DSSS system. A CW carrier was input into the DSSS receiver and slowly varied around the receiver frequency of 446 MHz. Then the DSSS transmitter was keyed and the effects of the CW carrier were observed. The CW carrier and DSSS signal were at equal power levels.

Figure 41 shows the spectrum analyzer plot of the mixer output resulting from the CW carrier at 446 MHz, acting alone on

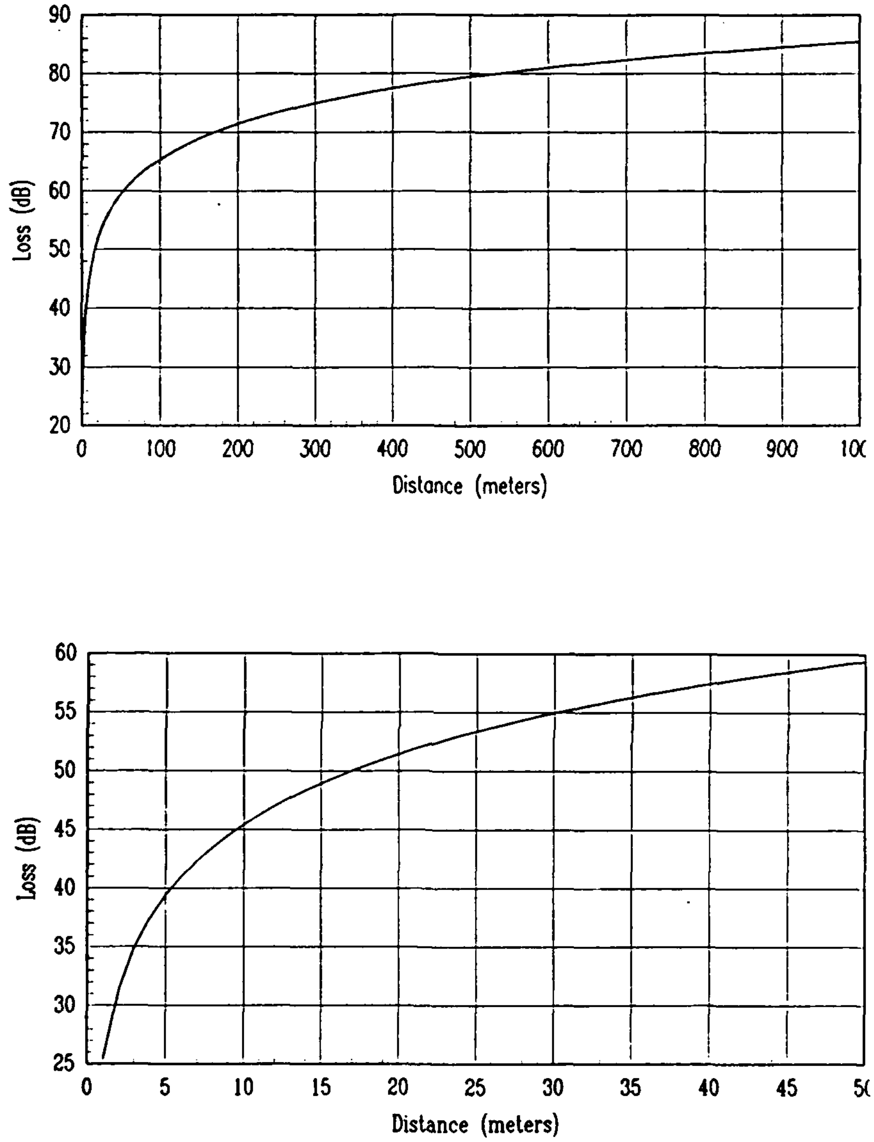


Figure 40. Free-Space Attenuation versus Distance

the DSSS receiver. The CW carrier is observed to be spread by the receiver PN code sequence. Figure 42 shows the plot of the mixer output resulting when both the CW carrier and the synchronized DSSS signal are input into the receiver. The CW carrier is not noticeable in Figure 42.

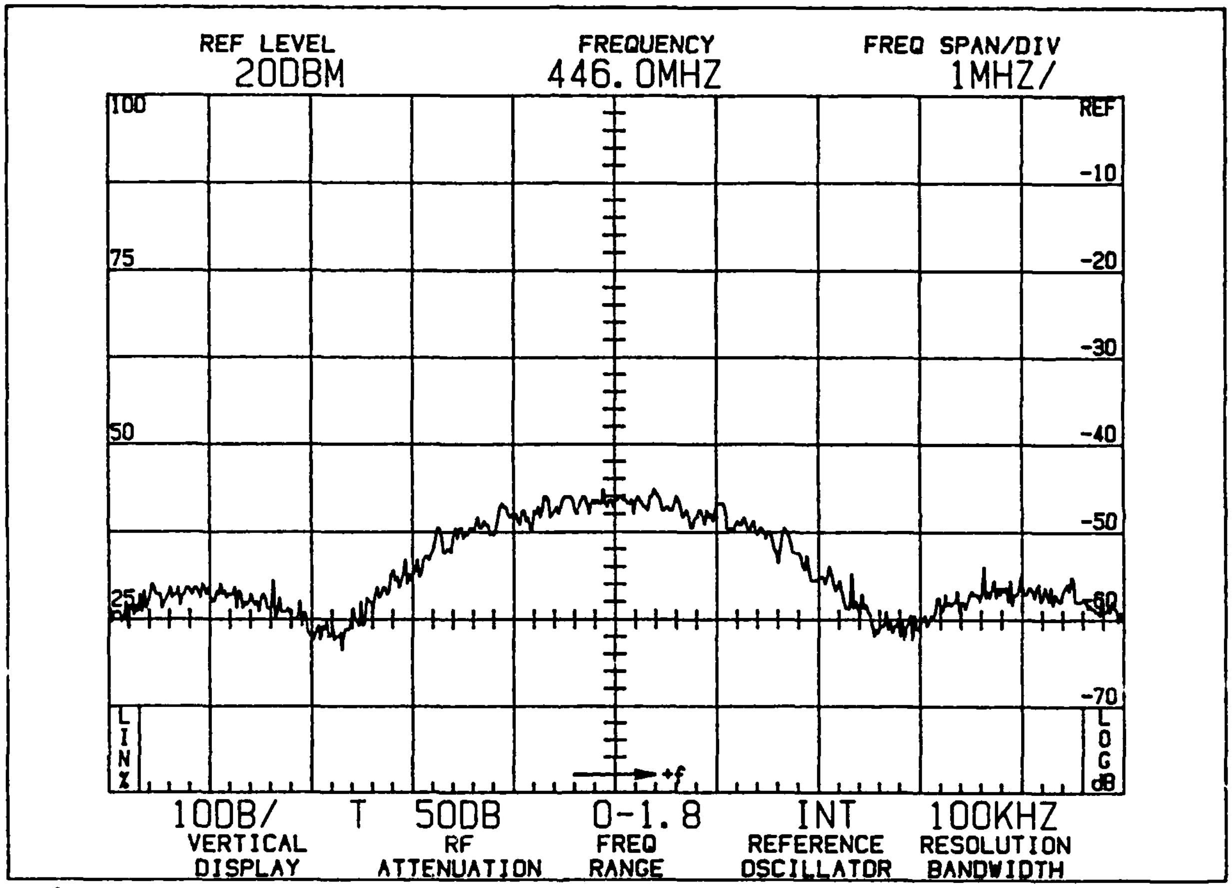


Figure 41. Receiver DBM Output with CW Tone Input (No DSSS Signal)

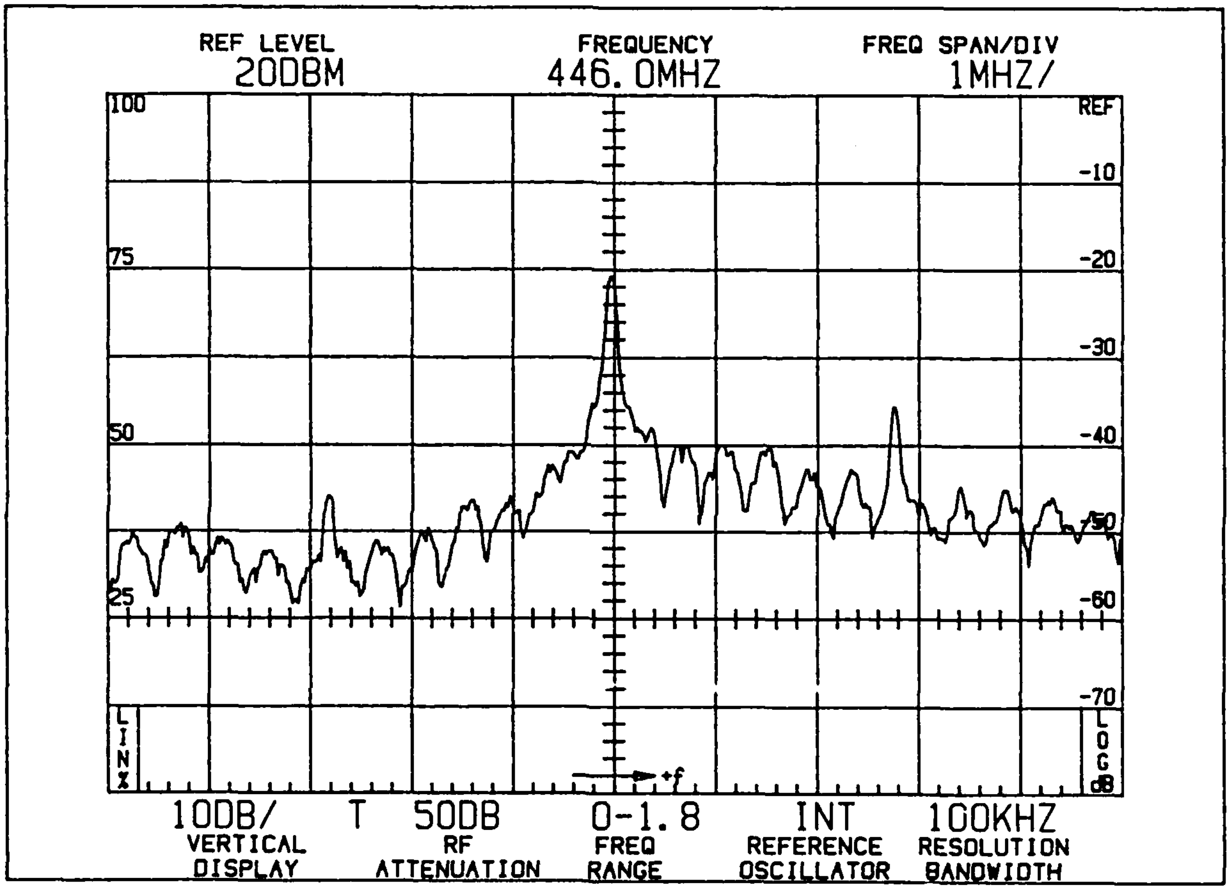


Figure 42. Receiver DBM Output with CW Tone Input (With DSSS Signal)

VI. Summary

Conclusions

The objectives of this research effort were fully met. The DSSS system, as described by Kesteloot (1), was constructed and evaluated. Some modifications were made to Kesteloot's system. Modular construction was used, the PN code generator was redesigned, and components were substituted for the transmitter final amplifier and the divide-by-40 device. The modular construction provides a useful test-bed for demonstrating spread spectrum concepts and allowing additional design concepts to be evaluated.

The synchronous oscillator provided a fast and easily implemented means of achieving direct-sequence spread spectrum synchronization. The measured system processing gain agrees favorably with the theoretical value. FSK was implemented at 300 bps and, allowing for poor receiver sensitivity, produced reasonably expected bit-error rate versus SNR curves. The range of the DSSS system was extremely limited; however, the range was predicted and verified prior to the field tests. The DSSS system was found to be unaffected by the presence of a CW carrier at the same input power and center frequency of the spread spectrum signal.

Although the limited range was disappointing, this does not detract from the research effort. A direct conversion receiver, such as used by the DSSS receiver, is simple, inexpensive, and easy to build. Commercial receivers requiring good sensitivity use a superheterodyne technique. Although it is not surprising that the DSSS receiver lacks good sensitivity, the research objectives were nevertheless met by a system that is easy to build within the time constraints of this effort.

Recommendations

It is recommended that additional research be devoted toward studying spread spectrum concepts and applications. The DSSS system developed here can be used as a starting point for further research. Specifically, the range of the DSSS system should be increased. This could be accomplished by increasing the output power and improving the receiver sensitivity. According to the curves of Figure 40, a path loss of 90 dB would extend the communication range to beyond 1 km. It would not be practical to overcome all this loss by the use of more transmitter power. It is suggested that the receiver be redesigned to include a 1st stage conversion to a 21.4 MHz IF. At this IF frequency it would be easier to add additional amplification, AGC, and investigate other synchronization techniques.

Although the synchronization oscillator performed quite well, it is necessary to compare its performance with other synchronization techniques. It is suggested that a similar injection oscillator process, using a first or second order phase-lock loop, be investigated and compared to the synchronous oscillator. A digital implementation of a synchronization technique, such as a surface acoustic wave device (SAW), could also be investigated.

Another area requiring additional research is to add a coherent phase demodulator to the receiver so that digital data could be carried by the system. Digital data which is imposed on the PN code sequence by modulo-2 addition, not digital data in the form of analog FSK, as performed in this study. This is the technique more commonly used for direct sequence spread spectrum.

The areas for further study using the DSSS system are unlimited. Quadrature phase shift modulation (QPSK) could be added and the spectral qualities of QPSK, off-set QPSK, and minimum shift keying (MSK) could be investigated. The DSSS system could be modified to frequency hop and the features of a hybrid spread spectrum system could be evaluated. Electronic counter-counter measures (ECCM) features could be fully evaluated using the DSSS system or a modified version. The DSSS system could be used as a source of radiation for studies relating to spread spectrum detection and parameter extraction, such as performed by MODAC research efforts.

The DSSS system developed by this research effort could be integrated into a packet radio experiment in the Amateur Radio Service using existing AFIT packet radio capabilities. The use of spread spectrum for this application has received wide attention as a means of eliminating frequency congestion. By adding a carefully managed spread spectrum protocol, it may be possible to greatly reduce "collisions", avoid interference, and add significantly to the repertoire of the packet system. Packet radio is gaining support in military applications for tactical use. These research activities will directly contribute toward furthering our knowledge of advanced communications techniques in support of current and future military applications.

Appendix A

DSSS Operating Instructions

This appendix provides basic operating instructions for the DSSS system as described in this report. Additional information is provided for those interested in using the DSSS system for demonstration, educational, or research applications.

Step 1 - Station Set-up

The DSSS system is a one-way UHF communications link. It is operated by placing the receiver and transmitter at different locations. The maximum separation of the DSSS transmitter and receiver units, as described, has been determined experimentally to be approximately 5 meters. The DSSS transmitter and receiver both require 120 vac. The system must is initialized by selecting a code polynomial and programming the same PN code polynomial into each unit; this is described in Step 2. A microphone, or other audio source, is connected to the transmitter to provide a source of information for transmission. Antennas are required for both receiver and transmitter. When power is applied to both units, transmission will begin when the push-to-talk button on either the microphone or the transmitter front panel is activated. The tune knob of the receiver must be adjusted until the receiver PN sequence has locked to the transmitter sequence.

For successful operation, it is important that each subsystem is interconnected properly. These interconnections are normally left unchanged. At the front panel of both the transmitter and receiver units, the CO REF must be patched to the CLK IN and the MIXER must be patched to the PN CODE OUT.

Note: The polynomial 301(octal) is the only FCC authorized PN code which may be generated by the DSSS system for operation in the Amateur Radio Service.

Step 2 - Understanding the DSSS System Front Panel

DSSS Transmitter

The DSSS Transmitter front panel is shown in Figure 43. Each of the front panel features are describe below:

CO REF: An output that provides a 2.7875 MHz clock source for the PN code generator. This output is coherently derived from the exciter and is precisely 1/160 of the carrier frequency. This TTL level output is normally patched to the PN code generator clock input (CLK IN).

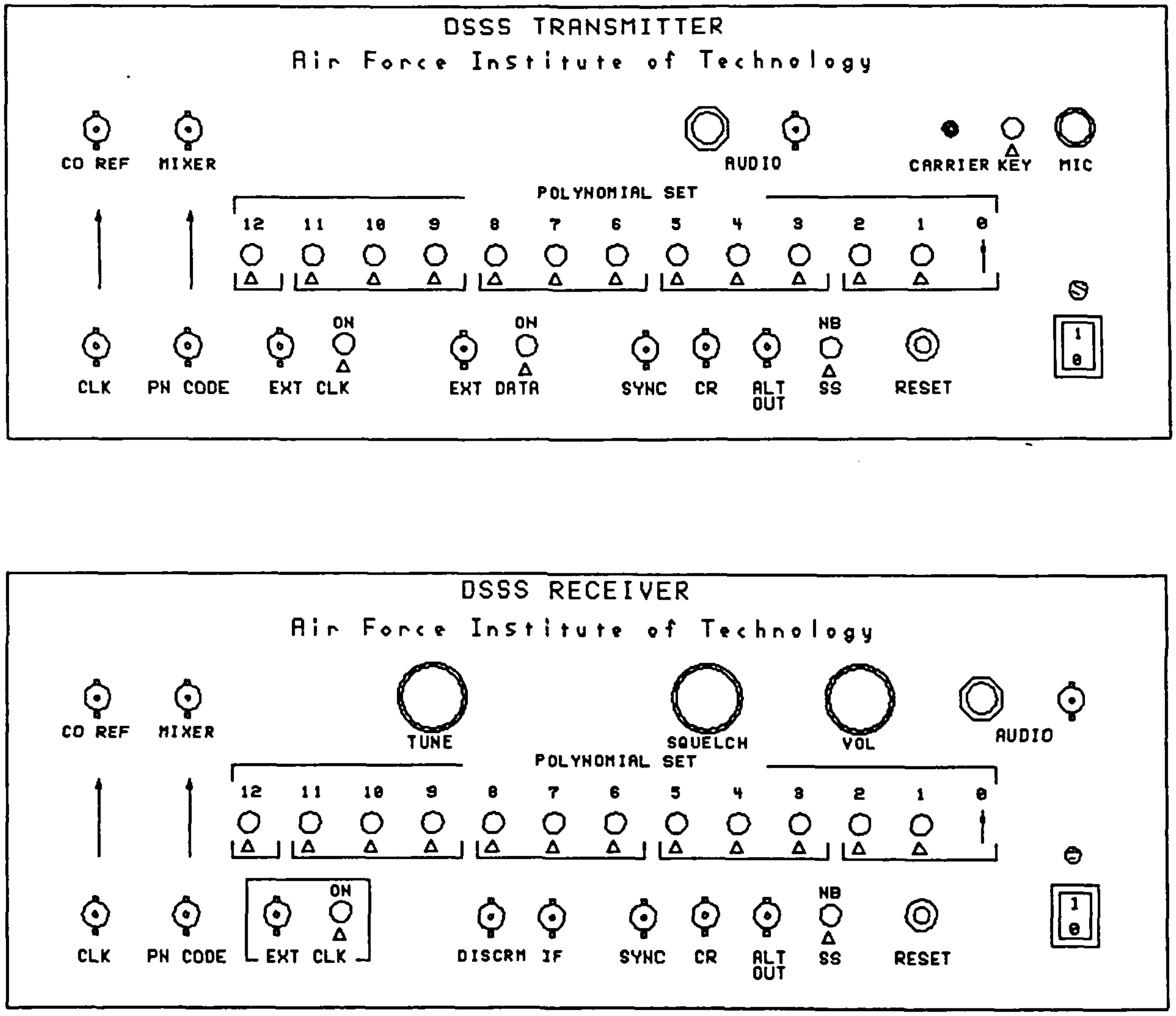


Figure 43. DSSS Transmitter and Receiver Front Panels

MIXER: An input to the transmitter double-balanced mixer. The output of the PN code generator (PN CODE OUT) is normally patched to this connector.

AUDIO: An input to the FM exciter. Two different connectors are provided: a BNC and a phone jack. A test tone or audio FSK is normally inputted. Any low impedance audio source capable of supplying 30 mv p-p across 2000 ohms may be used. Avoid inputting audio above 30 mv p-p. Although the FM exciter is provided with a deviation limiter to prevent over-modulation, distortion from excessive clipping may result.

CARRIER INDICATOR: An LED indicator that illuminates when the transmitter is keyed.

KEY: A 3-position toggle switch that will turn the transmitter on. The transmitter is off (unkeyed) when the switch is in the center position. In the up position the switch will remain engaged for continuous transmitting until returned to the center position. In the down position the switch provides temporary contact and will return to the center position when the switched is released.

MIC: A microphone input for the FM exciter. A low impedance dynamic microphone (500 - 1000 ohms) is recommended.

The microphone connector is a standard 4-pin connector providing both audio and push-to-talk keying circuits.

POLYNOMIAL SET SWITCHES: A series of 12 switches numbered 1 through 12 which are used to program the sequence polynomial. A polynomial tap is set when the switch is in the "up" position. There is no switch at position 0. Position 0 is always assumed to be up as indicated by the arrow.

CLK IN: The clock input to the PN code generator. This is a TTL level input. The clock input should not exceed 30 MHz.

PN CODE OUT: The sequence output of the PN code generator. This is a TTL level output.

EXT CLK: An input for an external clock signal which is enabled by the adjacent switch. In the DSSS system, the PN code generator receives the clock signal from the transmitter exciter or the receiver synchronous oscillator through the "CLK IN" input. This TTL level input allows the generator to be clocked by an external source.

EXT DATA: An external data input that is enabled by the adjacent switch. The purpose of this TTL level input is to provide for modulo-2 addition of a data source to the PN code sequence. This input allows experimentation in digital transmission of information.

SYNC: An output signal that provides a synchronization pulse at the end of each PN code sequence period. This signal is useful for measuring the sequence period for various code lengths. The TTL level SYNC output is useful in maintaining data and sequence synchronization when an external data source is used.

CR: A chip rate (CR) output for monitoring the generator clock rate. This TTL level output will normally drive a frequency counter.

ALT OUT: An alternate sequence output from the PN code generator. The primary output (PN CODE OUT) is taken from register stage 1. The alternate output is taken from register stage 4. Therefore, the two outputs are 3 bits delayed with respect to each other. This feature provides for experimentation into code shift keying (CSK). This is a TTL level output.

NB/SS: A switch used to disable the PN code generator by disabling the generator clock to all stages. When the PN code generator is used with the DSSS system, this switch is used to select from narrowband (NB) to spread spectrum (SS) operation.

RESET: A pushbutton switch that will cause the PN code generator to reset to the initial fill state. The initial fill state for the PN code generator is a "1" in the first stage followed by "0"s in the remaining stages.

POWER: A rocker switch which turns the DSSS Transmitter circuits on. The transmitter does not radiate until keyed.

DSSS Receiver

The DSSS receiver front panel is nearly identical to the transmitter front panel except as noted:

CO REF: An output from the synchronous oscillator which provides the clock source for the PN code generator. This output is a TTL level signal at approximately 2.7875 MHz to match the CO REF clock from the transmitter. Unless some other means of system synchronization has been provided, this output must be patched to the CLK IN connector.

TUNE: A control used for providing initial synchronization. The TUNE control adjusts the free-running frequency of the synchronous oscillator. The synchronous oscillator free-runs at approximately 111.5 MHz. The synchronous oscillator output is divided by 40 to produce the 2.7875 MHz CO REF signal. The TUNE adjustment is necessary to bring the synchronous oscillator free-running frequency close to that of 2.7875 MHz so that the oscillator will become synchronized and begin tracking the transmitted signal. Once the DSSS system has been synchronized, tuning is usually not necessary for hours of continuous or intermittent operation.

SQUELCH: A control for adjusting the signal strength at which audio will be passed to the audio connectors. The SQUELCH control eliminates much of the background noise that is present when no signal is being transmitted. The receiver squelch circuit has about 3 to 6 dB of hysteresis built in, so that once the squelch opens, the signal must drop 3 to 6 dB below the opening threshold before squelching again.

VOL: A control for adjusting the audio volume.

AUDIO: Audio output from the DSSS receiver. Two connectors are provided: a BNC and a phone jack. Normally a speaker or headphones are connected to the phone jack. The BNC connector is useful for measuring audio levels and distortion. FSK modulation may also be processed through this connector.

DISCRIM: A discriminator output from the narrowband FM receiver.

IF: An output from the output of the mixer. This is not truly an IF signal since the output is centered at 446 MHz. This output is intended to provide flexibility in the processing of the demodulated spread spectrum signal. This output may be used to circumvent the narrowband FM receiver for processing by an external receiver or device.

Step 3 - Establishing the Sequence Polynomial

Referring to Figure 43, the polynomial set switches must be set to the desired sequence polynomial. Table III lists some m-sequence polynomials. Reference 13, provides a complete list irreducible polynomials from which m-sequences can be determined. It is recommended that m-sequences be used with the DSSS system, however, other sequences such as Gold Codes and JPL Codes are possible.

> Note: The polynomial 301(octal) is the only FCC authorized PN code which may be generated by the DSSS system for operation in the Amateur Radio Service.

A polynomial is established by setting the corresponding feedback taps by placing the tap switches in the "up" position.

> Note: All polynomial set switches not representing feedback taps must be in the "down" position.

<u>Example:</u> Establish the sequence polynomial:

$$X^7 + X + 1 \tag{A1}$$

Place the switch positions as shown:

12	11	10	9	8	7	6	5	4	3	2	1
dn	dn	dn	dn	dn	up	dn	dn	dn	dn	dn	up

Sometimes a polynomial is represented in octal notation such as found in reference 13. The following is an example of establishing the sequence polynomial from an octal representation:

Example: Establish the sequence polynomial:

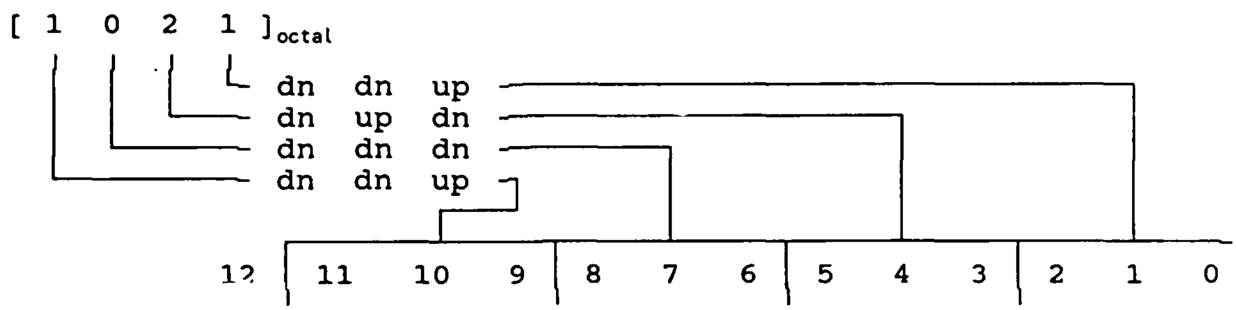
$$[\ 1\ 0\ 2\ 1\ ]_{octal} \tag{A2}$$

Beginning at the right with polynomial set position 0 in Figure 43, the polynomial set switches are segmented into groups of three, except for the last switch. These groups represent octal weights according to the following:

Octal Number	Switch Position		
0	dn	dn	dn
1	dn	dn	up
2	dn	up	dn
3	dn	up	up
4	up	dn	dn
5	up	dn	up
6	up	up	dn
7	up	up	up

> Note: There is no switch at position 0 and it is always assumed to be up.

Sequence polynomial [1 0 2 1]$_{octal}$ becomes:



<u>Verifying a Proper Output</u>. Connect channel 1 of a dual-trace oscilloscope to the PN CODE connector. A TTL compatible digital sequence will be present on the oscilloscope display. The oscilloscope must have a response that is compatible with the clock rate.

To confirm proper sequence length, connect channel 2 of the oscilloscope to the SYNC connector. Adjust the oscilloscope time-base until the period between two sync pulses can be observed and measured. The measured value will agree with the computed value (allowing for measurement inaccuracies).

The interval period between sync pulses can be computed as follows:

$$T_N = N \quad T_c \qquad \text{(A3)}$$

where

N = code sequence length

T_c = clock period

> Note: To ensure proper operation, fast rise and fall times consistent with good pulse generation, must be used.

<u>Step 4 - Transmitter Operation</u>

Connect approximately 20' of RG-58 coaxial cable to the transmitter at the BNC connector on the output of the RF amplifier/filter assembly. At the other end of the cable connect the Ringo AR-450, UHF antenna. The antenna may be mounted on a 10 foot mast for added elevation. The antenna and 10 foot mast should be mounted as high as practical and in the clear of surrounding obstacles.

Ensure that the front panel patches are connected from the CO REF to the CLK IN and the MIXER to the PN CODE OUT; and that a proper PN code polynomial has been set according to Step 3.

Connect the microphone to the MIC connector, or some other audio source to the AUDIO input connector.

Power the transmitter on by switching the power switch to the "1" position. You will observe the power indicator light illuminating when the transmitter is on.

Transmission will begin when the push-to-talk button on either the microphone or the transmitter front panel KEY switch is activated. You will observe the CARRIER LED illuminating when the transmitter is being keyed.

Step 5 - Receiver Operation

In a similar fashion, connect a Ringo AR-450, UHF antenna to the receiver through 20' of RG-58 coaxial cable.

Power the receiver on by switching the power switch to the "1" position. You will observe the power indicator light illuminating when the receiver is on.

Ensure that the front panel patches are connected from the CO REF to the CLK IN and the MIXER to the PN CODE OUT; and that a proper PN code polynomial has been set according to Step 3.

Before the transmitter has been keyed. Adjust the VOL control to about one-third of its rotation. Adjust the SQUELCH control clockwise until noise is heard in the receiver speaker. The VOL can now be adjusted to the operator satisfaction. Back the SQUELCH control off until the noise is eliminated. After the transmitter has been keyed, adjust the TUNE control until the receiver PN sequence has locked to the transmitter sequence. The transmitted audio will be heard in the speaker when synchronization has been achieved.

Verifying synchronization. Synchronization can be verified by connecting a spectrum analyzer to the output of the receiver mixer. Simply remove the cable which leads to the narrowband receiver and connect to the spectrum analyzer. Synchronization can be observed when a large correlation peak occurs at 446 MHz. This correlation peak and its associated sidebands can be seen in Figure 30.

Appendix B

Excerpts from

Federal Communications Commission

Rules and Regulations

(47 CFR Ch.I, 10-1-88 Edition)

Part 97 - Amateur Radio Service

SECTION 97.1 Basis and purpose

The rules and regulations in this part are designed to provide an amateur radio service having a fundamental purpose as expressed in the following principles:

(a) Recognition and enhancement of the value of the amateur service to the public as a voluntary noncommercial communication service, particularly with respect to providing emergency communications.

(b) Continuation and extension of the amateur's proven ability to contribute to the advancement of the radio art.

(c) Encouragement and improvement of the amateur radio service through rules which provide for advancing skills in both the communication and technical phases of the art.

(d) Expansion of the existing reservoir within the amateur radio service of trained operators, technicians, and electronics experts.

(e) Continuation and extension of the amateur's unique ability to enhance international good will.

SECTION 97.71 Spread spectrum communications

(a) Subject to special conditions in paragraphs (b) through (i) of this section, amateur stations may employ spread spectrum transmissions to convey information containing voice, teleprinter, facsimile, television, signals for remote control of objects, computer programs, data, and other communications including communication protocol elements. Spread spectrum transmission must not be used for the purpose of obscuring the meaning of, but only to facilitate communication.

(b) Spread spectrum transmissions are authorized on amateur frequencies above 420 MHz.

(c) Stations employing spread spectrum transmissions shall not cause harmful interference to stations of good engineering design employing other authorized emissions specified in the table. Stations employing spread spectrum must also accept all interference caused by stations of good engineering design employing other authorized emissions specified in the table. (For the purposes of this sub-paragraph, unintended triggering of carrier operated repeaters is not considered to be harmful interference. Nevertheless, spread spectrum users should take reasonable steps to avoid this situation from occurring.)

(d) Spread spectrum transmissions are authorized for domestic radio communication only (communication between points within areas where radio services are regulated by the U.S.Federal Communications Commission), except where special arrangements have been made between the United States and the administration of any other country concerned.

(e) Only frequency hopping and direct sequence transmissions are authorized. Hybrid spread spectrum transmissions (transmissions involving both spreading techniques) are prohibited.

(1) <u>Frequency hopping</u>. The carrier is modulated with unciphered information and changes at fixed intervals under the direction of a high speed code sequence.

(2) <u>Direct sequence.</u> The information is modulo-2 added to a high speed code sequence. The combined information and code are then used to modulate a RF carrier. The high speed code

sequence dominates the modulation function, and is the direct cause of the wide spreading of the transmitted signal.

(f) The only spreading sequences which are authorized must be from the output of one binary linear feedback shift register (which may be implemented in hardware or software).

(1) Only the following sets of connection may be used:

Number of stages in shift register	Taps used in feedback
7	[7 , 1]
13	[13 , 4 , 3 , 1]
19	[19 , 5 , 2 , 1]

(The numbers in brackets indicate which binary stages are combined with modulo-2 addition to form the input to the shift register in stage 1. The output is taken from the highest numbered stage.)

(2) The shift register must not be reset other than by its feedback during an individual transmission. The shift register output sequence must be used without alteration.

(3) The output of the last stage of the binary linear feedback shift register must be used as follows:

(i) For frequency hopping transmissions using x frequencies, n consecutive bits from the shift register must be used to select the next frequency from a list of frequencies sorted in ascending order. Each consecutive frequency must be selected by a consecutive block of n bits. (Where n is the smallest integer greater than $\log_2 x$).

(ii) For a direct sequence transmission using m-ary modulation, consecutive blocks of $\log_2 m$ bits from the shift register must be used to select the transmitted signal during each interval.

(g) The station records shall document all spread spectrum transmissions and shall be retained for a period of one year following the last entry. The station records must include sufficient information to enable the Commission, using the information contained therein, to demodulate all transmissions. The station records must contain at least the following.

(1) A technical description of the transmitted signal.

(2) Pertinent parameters describing the transmitted signal including the frequency or frequencies of operation and, where applicable, the chip rate, the code, the code rate, the spreading function, the transmission protocol(s) including the method of achieving synchronization, and the modulation type;

(3) A general description of the type of information being conveyed, for example, voice, text, memory dump, facsimile, television, etc.;

(4) The method and, if applicable, the frequency or frequencies used for station identification.

(5) The date of beginning and date of ending use of each type of transmitted signal.

(h) When deemed necessary by an Engineer-in-Charge of a Commission field facility to assure compliance with the rules of this part, a station licensee shall:

(1) Cease spread spectrum transmission authorized under this paragraph;

(2) Restrict spread spectrum transmissions authorized under this paragraph to the extent instructed;

(3) Maintain a record, convertible to the original information (voice, text, image, etc.) of all spread spectrum communications transmitted under the authority of this paragraph.

(i) The peak envelope power at the transmitter output shall not exceed 100 watts.

SECTION 97.84 Station identification

(a) Each amateur radio station shall give its call sign at the end of each communication, and every ten minutes or less during a communication.

(g) The identification required by this section shall be given on each frequency being utilized for transmission and shall be made in one of the following manners:

(1) By telegraphy using the international Morse code (if this identification is made by an automatic device used only for identification, the code speed shall not exceed 20 words per minute);

(2) By telephony using the English language (the Commission encourages the use of a nationally or internationally recognized standard phonetic alphabet as an aid to correct telephone identification);

(5) When transmitting spread spectrum, by narrow band emission using the method described in paragraph (g)(1) or (2) of this section, narrow band identification transmissions must be on only one frequency in each band being used. Alternatively, the station identification may be transmitted while in spread spectrum operation by changing one or more parameters of the

emission in a fashion such that CW or SSB or narrow band FM receivers can be used to identify and sending station.

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Vita

James P. Stephens was born 15 July, 1947 in Steubenville, OH. He graduated from Follansbee High School in 1965. Mr. Stephens received a BSEE from West Virginia Institute of Technology in 1969. Upon graduation he was employed by the Federal Communications Commission where he served as a field engineer in the Norfolk, Detroit, and Cincinnati Field Offices. His most recent FCC assignment was that of Engineer-in-Charge, Cincinnati Field Office. In 1982, Mr. Stephens left the FCC and was employed as an electronics engineering analyst for the Foreign Technology Division, Wright-Patterson Air Force Base. He performed reverse engineering to assess reliability, capability, and effectiveness of foreign communications systems. Mr. Stephens also serves as a part-time instructor in the Electrical Engineering Technology program at Miami University, Middletown Branch. While employed with FTD, Mr. Stephens became a part-time graduate student at the School of Engineering, Air Force Institute of Technology. In August 1989, he attended AFIT, full-time, under the Air Force Systems Command, Long-Term Full-Time training program.

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The purpose of this study is to construct and evaluate the performance of a direct-sequence spread spectrum (DSSS) system. The system, based upon a previously published design, uses a special type of injection-locked oscillator called a "synchronous oscillator" for code synchronization. The DSSS system was constructed in a manner that provides a test-bed for demonstrating spread spectrum principles and allows researchers to evaluate their own sub-system design concepts.

The DSSS system, designed as a one-way link in the 420-450 MHz band, is constructed to operate in accordance with Federal Communications Commission rules and regulations pertaining to the Amateur Radio Service (Part 97). Unlike conventional DSSS systems which combine digital data with a pseudorandom (PN) code sequence, the system described here directly modulates an FM modulated Carrier with the PN code sequence.

The criteria used for evaluation are synchronization time, processing gain, and probability of bit-error rate. Because the DSSS receiver uses an inexpensive and practical direct conversion process before despreading, the receiver lacks good sensitivity. In spite of the limited range of the system, fundamental concepts of DSSS were evaluated, the measurements agreed favorably with theoretical values, and all research objectives were met.